Characterizing the Exhaust Plume of the Three-Electrode Micro Pulsed Plasma Thrusters

THESIS

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Abstract

There are several kinds of space propulsion device such as arcjets, Hall thrusters, ion thrusters and magnetoplasma dynamic thrusters (MPD). They all have their own ranges of performance measured as efficiency, specific impulse and thrust. The magentoplasma dynamic thrusters have the potential to generate high levels of thrust at very high specific impulses but require a relatively massive power supply. To provide this performance without the penalty of a heavy power supply, these devices are often employed as pulsed plasma thrusters. The pulsed plasma thruster (PPT) is an electric propulsion device using electric power to ionize and electromagnetically accelerate plasma to high exhaust velocity providing the high specific impulse levels, typically using polytetraflouroethalene (PTFE). PTFE has the advantage of being inert and nontoxic, giving the PPT system an additional benefit of being one of the safest propulsion systems for spacecraft. This research investigated the plume characteristics of a new PPT design, three-electrode micro PPT developed recently by AFRL. The one tested here has a 3.175 mm (1/8") diameter tube. There are three major benefits of using a three-electrode micro PPT. The most important benefits include minimal shot to shot variations, decreasing required voltage and increased controllable firing frequency. Using three concentric electrodes provides very precise impulse bits with a great degree of operability. The thruster was put in a vacuum chamber capable of pressure level as low as 10^{-8} torr to simulate satellite operating environments in space. The importance of studying

micro PPTs is directly related to the satellite design trend toward developing smaller space vehicles, which require precise impulse-bits.

In characterizing these thrusters, particulate velocities in the plume were measured using a stereoscopic approach to get accurate velocity and divergence information. This information directly applies to the performance of these thrusters. Both velocity and angle data were analyzed for normal distributions at each thruster operating condition. The velocity and angle distributions are also compared between operating conditions identifying the energy effect on these distributions. The results show that the three-electrode micro-PPT is more reliable than two-electrode micro-PPT and the operating energy range from 2 to 4.5 Joule is proper value to operate it. This research also shows that the angle distribution is similar to previous mass deposition distributions and the faster particles have shallower angles than that of slower particles. Finally, the energy did not give appreciable effect on angle and velocity distributions and have the Isp value range from 25 to 35 sec of the large particles from the average exit velocity.

Acknowledgments

Most of all, I sincerely appreciate to my thesis advisor, Lt Col Richard Branam for his guidance whenever I encounter the trouble during the research. I also give my thanks to AFIT lab staff, Jay Anderson, Christopher Zickefoose, Wilbur Lacy and Sean Miller for their effort to help me when dealing the lab apparatus. Finally, I've got unique opportunity to get my honorable master's degree because of R.O.K Air Force and my family.

Seo Myeongkyo

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CHARACTERIZING THE EXHAUST PLUME OF THE THREE-ELECTRODE MICRO PULSED PLASMA THRUSTERS

I. Introduction

I.1. Background

There are several kinds of space propulsion device such as arcjets, Hall thrusters, ion thrusters and magnetoplasma dynamic thrusters (MPD). They each have found their niche based primarily on their own specific performance; efficiency, specific impulse and thrust. The pulsed plasma thruster (PPT) is a magnetoplasma dynamic device relying on electronic pulsing to minimize the massive power system requirements of these types of devices. They use the electric power to ionize and electromagnetically accelerate plasma to high exhaust velocity providing the high specific impulse levels. Often, these devices use a solid propellant with polytetraflouroethalene (PTFE) as a preferred material. PTFE has the advantage of being inert and nontoxic, giving the PPT system an additional benefit of one of the safest propulsion systems for spacecraft. Because of these advantages, PPTs have a long history of reliable space flight operation.[1] The first PPT flight was the Soviet Zond-2 spacecraft in 1964. In the United States, PPT development work for the present solid-state PTFE devices began in the 1960s and led to the first U.S. flight of a PPT aboard the Lincoln Experimental Satellite (LES 6) in 1970. The system performed flawlessly in an East–West station-keeping role over its five-year life. The success of the LES-6 led to consideration of the PPT for other missions. One such mission was the U.S. Navy's NOVA navigation satellites. PPTs were found to be well suitable to provide drag compensation for this mission. Three NOVA spacecraft were

launched between 1981 and 1988. Two PPT systems per spacecraft provided drag make-up propulsion for seven years on each of the three NOVA spacecraft in low earth orbit (LEO). In 1995, NASA Lewis Research Center (now Glenn Research Center) initiated a program with Primex Aerospace Co. (now Aerojet-Redmond Operations) to develop, fabricate, and flight qualify a PPT. The result is the Earth Observer-1 (EO-1) PPT, which performed flawlessly starting in February of 2001.

With the trend in satellite design towards small, low cost, satellite constellations, the need for miniaturizing the PPT (and other thruster systems) is apparent. The U.S. Air Force Research Lab (AFRL) at Edwards Air Force Base undertook an effort to miniaturize the pulsed plasma thruster (two electrode micro-PPT). Subsequently, the lab also developed a three-electrode design in a desire to reduce shot-to-shot variability in the self-triggered device. This design allows for the elimination of the external igniter necessary in two electrode designs. Much work has been accomplished to date to measure the characteristic of PPTs focusing on propellant consumption rate, plasma velocity, plasma density, temperature of propellant surface, and charred Teflon surfaces. These measures result in a means to predict performance in terms of specific impulse, efficiency and thrust.

I.2. **Problem Statement**

Three-electrode micro-PPTs are a new version of two electrode micro-PPTs devices as mentioned before. Performance predictions and contamination expectations are essential characteristics needed by satellite designers. In order to focus on thruster specific impulse, thrust and efficiency, measuring the exhaust velocity or impulse bit and

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propellant c onsumption rate is e ssential. While thi s is not always pos sible to measure directly, focusing on t he e jected m ass f rom t he P PT pr ovides s ignificant i nformation allowing determination of these performance statistics. Specifically, focusing on exhaust angle distribution and velocity of the exhaust particles is the emphasis of this work.

I.3. **Research Objectives/Questions/Hypotheses**

1. One of ou r obj ectives i s t o bui ld a nd t est t hree-electrode mic ro-PPT, va ry input voltage to establish operating capabilities

2. Assess the ve locity and angle of t he pa rticles l eaving from a t hree-electrode micro-PPT and construct distribution functions of pa rticle velocities and exit angles to allow for prediction of contamination and performance impacts

3. Figure out energy effect on velocity and angle distribution.

I.4. **Methodology**

The three-electrode m icro-PPTs were put i n a be ll j ar va cuum c hamber. High speed imaging s ystems c aptured three di mensional images of the pa rticles f rom the P PT's exhaust s urface t o determine ve locity. To make a r eliable t hree-electrode m icro-PPT circuit, a high vol tage pul se de vice i s us ed t o make s eed ionization for the intermediate discharge. A f unction generator provided the s ignal t o hi gh vol tage p ulse a nd t wo cameras at the same time for firing the thruster and taking pi cture of thr ee di mensional images.

I.5. **Preview**

The next chapter focuses on the background knowledge of the two and three electrode micro PPT designs and also shows previous tests for the two electrode micro PPT. In

chapter 3, equipment such as the vacuum chamber, high speed cameras, the function generator and the high voltage pulse are described in detail along with the experimental setup for this research. Chapter 4 shows the result of the three-electrode micro-PPT operability and velocity/angular distribution of the particles from the three-electrode micro-PPT design at the different operating conditions. This chapter points out differences in the results with operating condition. The last chapter presents the conclusion of this study and recommendations for future research.

II. Literature Review

II.1.   **Chapter Overview**

In this chapter, we will present the history of PPTs and previous research. Introducing the differences between standard PPTs and micro PPTs is necessary for explaining the concept of a micro PPT and the unique utility of these devices. It is also useful to discuss relevant diagnostics used for PPTs to measure performance and plume characteristic.

II.2.   **History of PPT**

Antropov and Khrabrov in the USSR developed two PPT designs, one with an electromagnetic and the other with a thermal acceleration mechanism.[2] The latter type proved practical and was the design for the PPT used on the Zond-2 spacecraft in 1964. The first U.S. satellite using PPTs for attitude control was LES-6 on Sept. 26, 1968. This flight unit was a breech-fed design providing 26μN of thrust at a specific impulse of 312 s.[1] The success of the PPT on LES-6 led to other missions for these thrusters. In particular, the U.S. Navy's NOVA navigation satellites, operated between 1981 and 1988, using PPTs for drag compensation. The NASA Lewis Research Center (now Glenn Research Center) started a program with Primex Aerospace Co. (now Aerojet-Redmond Operations) to develop the Earth Observer-1 (EO-1) PPT, which performed flawlessly. Due to satellite design trends increasingly moving towards small, low cost, satellite constellations; miniaturizing the PPT (and other thruster systems) was needed. PPTs could be employed to provide formation keeping, maneuvering, orbit maintenance, and attitude control for smaller satellites.

A precise and predictable impulse bit is needed for microsatellites to support missions like formation flying, space based surveillance, space control, and on-orbit satellite servicing. In response to this need, the Air Force Research Laboratory developed a micro pulsed plasma thruster. Micro pulsed plasma thrusters have been developed and tested in two basic designs; triggered micro-PPT and self-triggered micro-PPT. The triggered micro-PPT uses a pulse of energy at the propellant face to drive a surface discharge. The self-triggering micro-PPT uses the high voltage directly to initiate the spark. The transition to a full surface discharge is through a surface breakdown. The triggered micro-PPT and the self-triggered micro-PPT reduced mass by a factor of about 10 and 60 from a standard PPT, respectively. The main failure of a triggered micro-PPT is the high voltage triggering switch. It can be protected through a cautious choice of circuit energy, voltage, and current but still tends to be a weak point in this design. Another major flaw in the triggered design is the occasional trend to gouge out a localized area of propellant. This results from having difficulty in evenly distributing the energy across the propellant face area. This flaw can lead to extra propellant usage. For these reasons, a self-triggering micro-PPT design has advantages as well as simpler electronics and lower mass.

AFRL has focused on propellant ablation rates suggesting the design criteria are to attain a desired steady-state propellant ablation characteristic. The discharge energy to surface area ratio and the current density at the inner electrode have to be sufficient to drive the PPT function properly. The micro-PPT efficiency turns out to be a trade-off between geometry (such as propellant area and inner electrode diameter) and discharge energy. These parameters directly affect the ablation rate characteristics.

While the lab initially developed these thrusters in-house, other work progressed to develop thrusters in the 100W range by CU Aerospace. Teamed with the University of Illinois at Urbana–Champaign and Unison Industries, the PPT-10 and PPT-10.1 were built relying on side-fed propellant systems. These coaxial pulsed plasma thrusters are based on the previous PPT-4 and PPT-7 thruster designs. These thrusters used energy levels between 40 and 80 J generating several mNs of thrust with a specific impulse of 800s. Table 1 presents PPT programs chronologically from Zond-2 in 1964 to Falconsat-3 in 2007.

Table 1: PPT Programs [3]

Program	Year	Energy	Voltage	Program	Year	Energy	Voltage
Zond-2	1964	50 J	1000 V	TIP-III	1976	20 J	1630 V
LES-6	1968	1.85 J	1360 V	NOVA-1	1981	20 J	1630 V
LES-7	~1970	20 J	?	ETS-IV	1981	2.25 J	1680 V
SMS	~1973	8.4 J	1450 V	MDT-2A	1981	4 J	2000 V
LES-8/9	~1973	20J(15J)	1370 V	NOVA-3	1984	20 J	1630 V
UAP-1	1974	30 J	1450 V	NOVA-2	1988	20 J	1630 V
UAP-2	1974	30 J	1450 V	EO-1	2000	8-56 J	<1700 V
LES-8/9	~1975	20 J	1530 V	Dawgstar	2002	5 J	2770 V
Millipound	1973-80	750 J	2500 V	AF µPPT	2003	1.25-6 J	2500-5400V
TIP-II	1975	20 J	1630 V	Falconsat 3[4]	2007	1.96J	-

II.3.   **Comparison of a standard PPT with micro-PPT (two and three-electrode design)**

Both PPTs are electric propulsion devices utilizing electric power to ionize and accelerate a plasma electromagnetically using solid propellant. The standard PPT consists

of a bar of polytetraflouroethalene (PTFE) propellant, spring, power processing unit

(PPU), capacitor, spark plug, anode and cathode (Figure 1). The spring pushes the

propellant, the only moving part, to replenish when the propellant face is consumed. A

PPU charges a capacitor to voltages using unregulated power from the spacecraft bus.

The PPU also supplies a high voltage pulse to a spark plug, used for triggering the

discharge. Once the discharge ignites, the energy stored in the capacitor feeds a high

current plasma discharge. This discharge ablates and ionizes a small amount of the

propellant face and accelerates it to high exhaust velocities using the Lorentz force[5]. The

Lorentz force results from the current and the self-induced magnetic field, which can be

expressed as below

$$F = qE' = q(E + v \times B)$$
(1)

F = Lorentz force (N)

q = Charge of moving particle (C)

E' = Effective electric field (V/m)

E = Applied electric field (V/m)

v = Velocity of particle (m/s)

B = Magnetic field (T)

The current-magnetic field interaction accelerates the ionized plasma. Another

component of thrust comes from the thermal expansion of non-ionized vapor resulting in

a much lower exhaust velocity.[6] This exhaust flow is often considered a loss when

considering specific impulse as is the solid particulates exiting the PPT. An ideal thruster would completely vaporize and ionize all of the propellant.

Figure 2 shows a simple schematic of the two-electrode micro-PPT[7]. In this configuration, a capacitor is connected to the coaxial propellant unit. The propellant consists of a central conductive rod functioning as the cathode and an annulus of PTFE encasing the cathode. The anode tube encloses the propellant. The major difference between the standard PPT and the two-electrode micro-PPT lies in the electronics. The micro-PPT uses only one circuit with one DC-DC converter. The capacitor charged by the DC–DC convertor supplies high voltage potential between the anode and cathode. When the thruster discharges, propellant ablates away, ionizes, and accelerates same as a standard PPT. The self-triggered micro-PPT discharge initiates when the electrode voltage exceeds the surface breakdown voltage across the propellant face. Traditional PPTs trigger the discharge using the external igniter plug which supplies a small amount of seed plasma to increase the conductivity across the face of the propellant.

A three-electrode micro-PPT was recently developed by AFRL.[8] Figure 3 shows the schematic of a three-electrode micro-PPT. The electrodes are referred to as outer, intermediate and center as shown in Figure 3. The center electrode is enclosed by a small annular tube of propellant, which is encased by the intermediate electrode. This intermediate electrode is also enclosed by a larger annular propellant tube, which is then surrounded by the outer electrode tube. The intermediate discharge between the central and intermediate electrode provide seed ionization plasma. This plasma reduces the resistance along the entire face of the propellant. The higher energy for main discharge

between the intermediate and outer electrode follows directly behind this initial plasma formation.

Using the three-electrode design has three major benefits. First, the energy of the main discharge now has minimal shot-to-shot variation decreasing the possibility of carbonization on the propellant face. Second, the seed ionization from the trigger discharge significantly decreases the voltage required on the main discharge to initiate the main pulse. For example, the trigger discharge will use about 1/50 the energy of the main discharge. Three-electrode micro-PPTs need relatively low voltage potentials (below 3000 V) in applications of 6.35 mm (1/4") diameter propellant tubes. Without a three-electrode design, the discharge across a 6.35 mm (1/4") diameter propellant requires up to 40,000 V to initiate the propellant surface ablation. Operating at lower voltages means we can reduce the mass of the electronics and therefore the thruster. A third advantage highlights the robustness of the design. The three-electrode design allows for better controllability. Firing frequency can be increased by decreasing the resistance in the trigger circuit or by increasing the output current of the PPU.
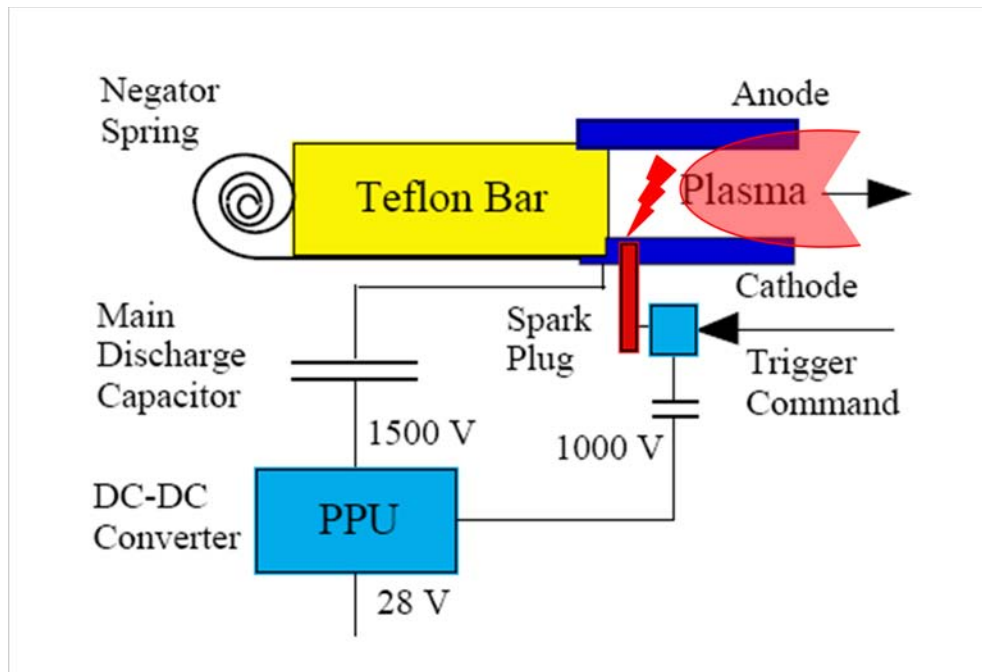
Figure 1: Standard Pulsed Plasma Thruster[9]
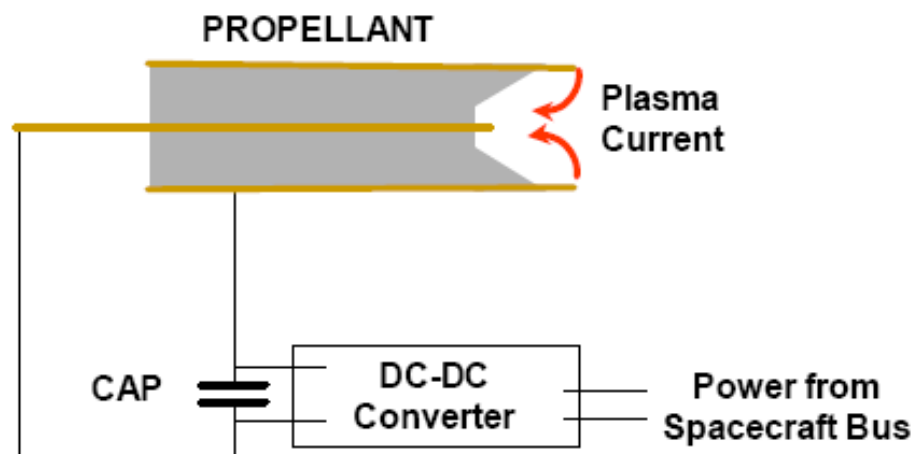
Figure 2: Two-electrode micro-PPT[7]
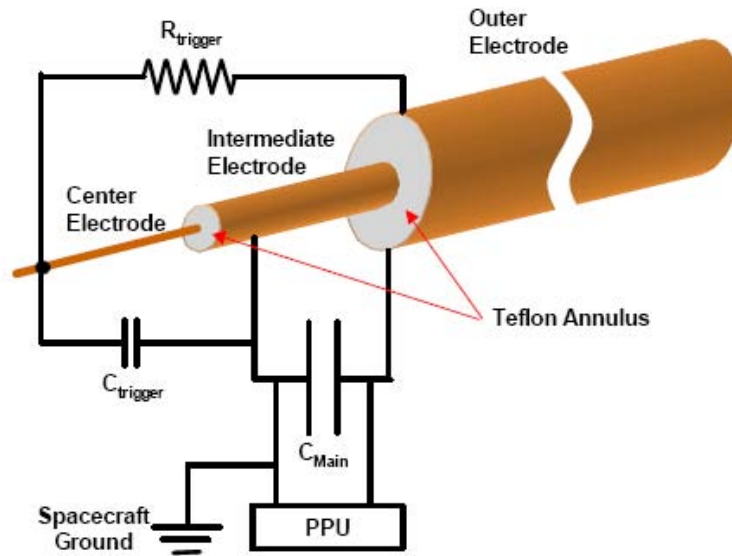
Figure 3: Three-electrode micro-PPT[7]

II.4.   **Optimization issue and modeling for micro PPT**

Micro-PPT operation depends on the energy and propellant tube geometry as mentioned earlier. Discharge uniformity (azimuthal and radial) is considerably affected by the both discharge energy and thruster size. The current constriction and anode spot formation phenomena is related to azimuthal non-uniformity which occurs when the discharge current or thruster tube size surpass some critical value.[10] Discharge non-uniformity results in a much higher ablation rate and decreases the potential specific impulse. In contrast, a small discharge current leads to strong charring and radial non-uniformity, which will eventually lead to thruster failure. The main reason of the charring was initially related to carbon back-flux. Thus, by adjusting the conflicting requirements between large (to prevent charring) and small energy (to prevent current constriction), the thruster geometry and discharge energy can be optimized.

University of Michigan and AFRL have published models for a micro-PPT.[11] They developed models including plasma generation, flow and expansion in the near field. They studied the plasma acceleration by the electromagnetic force and magnetic field dispersion into the plume. The propellant surface formed an inverse cone with a peak at the central electrode resulting from maximum temperature and ablation rate at the center of propellant. A comparison between the model and experiment for ablation depth and ablation profile showed similar results.

II.5.   **Measuring the Particle velocity and angle distribution of the two-electrode micro-PPT**

Sakir Tirsi employed a technique taking high-speed images of the exhaust plume from different angles to investigate exhausted particulate velocities.[12] He determined the speed of the particles with these images and characterized the exhaust plume angle with respect to the propellant face. Experiments were conducted at a small vacuum chamber at AFIT. The captured data was evaluated frame by frame. Discernible particles were selected with the purpose to create a velocity profile. Many particles were needed for reliable statistics. Velocities were calculated using two techniques. The first method measured pixel length of the particle streaks in any given image. This pixel length divided by the image exposure time gives a relatively accurate velocity of the particles. The second technique is to capture the same particle in two consecutive frames. This method is useful for the slower particles because of relatively longer times between frames. Figure 4 is an example of three consecutive images of a single discharge. Figure 5 shows an example of how Tirsi used the data to determine velocity and plume angles.

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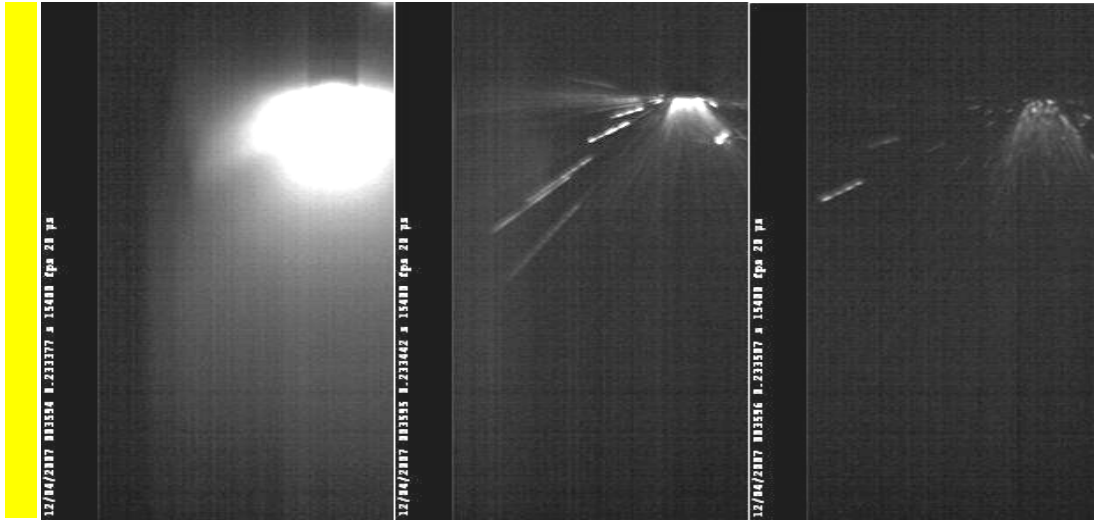
Figure 4: Consecutive Images Taken at 15400 fps and 20 μs Exposure Time
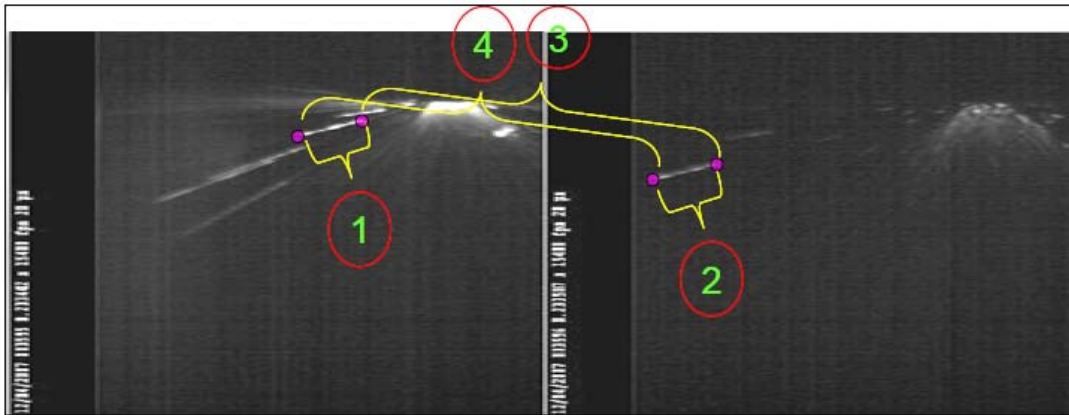
Figure 5: Velocity and Angle Measurements from Images

Figure 6 shows the distribution for the data collected for a 35μs exposure time. This

distribution follows a Gaussian distribution for all the particles collected (Figure 7).

These two figures show different exposure times does not change the distribution

relationships, thus this method does not introduce any error into the measurements. For

the higher velocity particles, more data is required to get a complete picture. In this work,

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the particles faster than 400m/s and 800m/s contributed only 11% and 0.5%, respectively.

The data previously collected (Figure 6 and Figure 7) only represents a two dimensional

velocity of the particles, a limitation of having images from only one position.
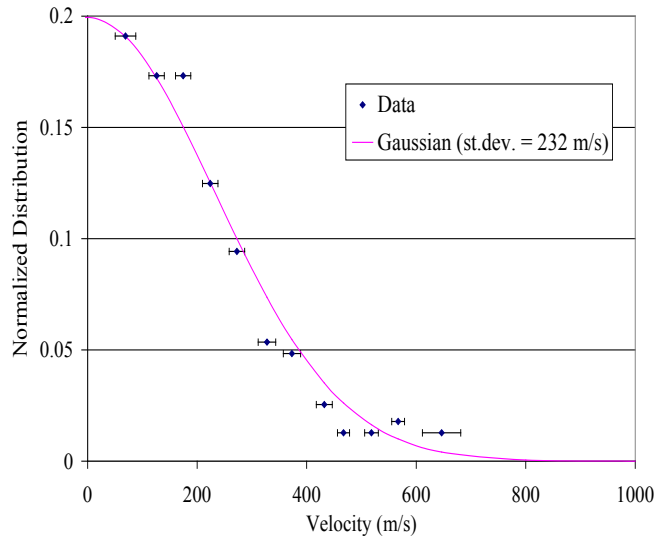
Figure 6: Particle Velocity (Magnitude) Distribution 35µs
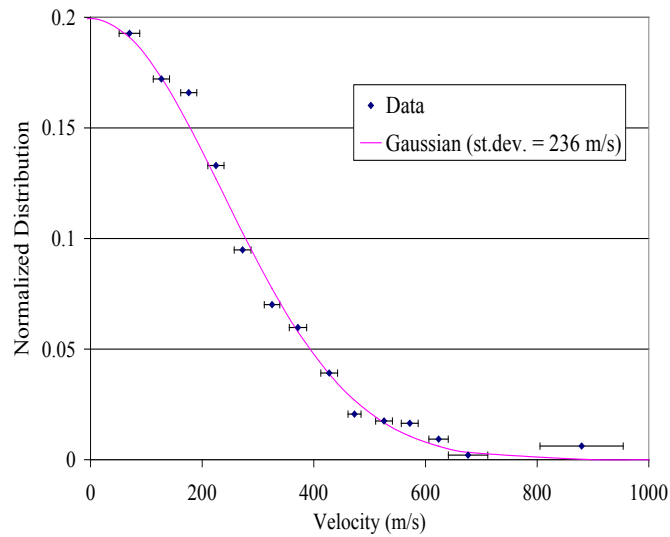
Figure 7: Velocity (Magnitude) Distribution for All Particles

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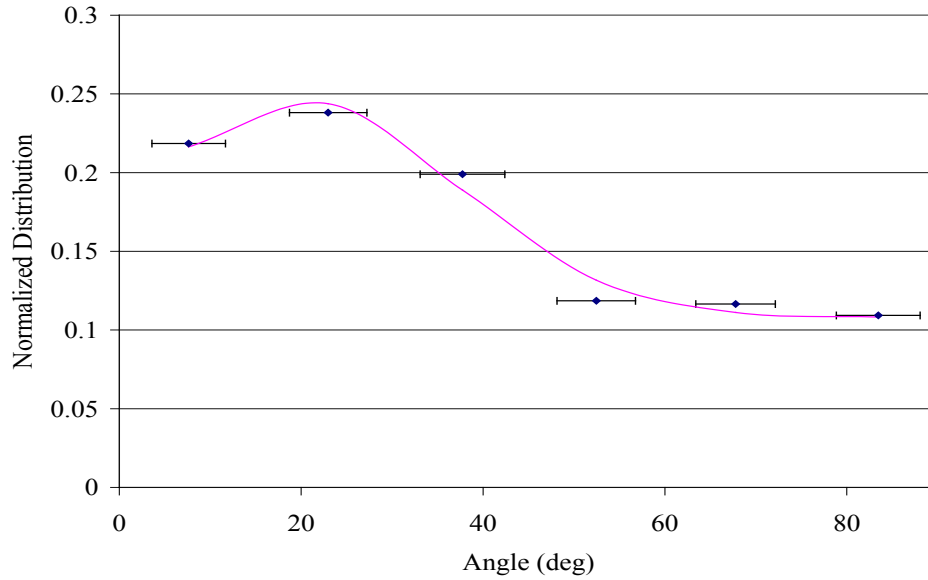
Figure 8: Normal Distribution for Particle Angles

The angle distribution also has been analyzed using the same results (Figure 8). This information shows particle departures were peaking around 30 degrees from the centerline for the self-triggered, two-electrode design. A concern with thrusters of this type is the relationship between the particle velocity and departure angle. Tirsi classified the particles slower than 200 m/s, slower than 300 m/s, faster than 300 m/s and faster than 500 m/s. Figure 9 shows the distribution for slow particles exhibiting the same tendency as seen for the distribution for all angles (Figure 8). This results means the slow particle distribution dominates the distribution for all the particles.

Figure 10 shows faster particles (>500m/s) leave the thruster face with a slightly narrower angle (20 degrees) comparing to the slow particles (25 degrees). In capturing the fast moving particles, Tirsi had to reduce the lapse time of 74 µs between frames to 35 µs. The associated frame rate is 28,500 fps. At higher frame rates, the camera is not able to retain the same resolution, reducing the obtainable capturing area to a resolution

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height of only 116 pixels. This restriction hampered the data capturing ability requiring

more data captures to provide valuable data. Figure 11 is an example of images taken at

these settings (28,500 fps and 16μs exposure time). The first image is saturated by the

spark. The second and third images show the same particle as it moved away from the

thruster, moving at 258 m/s. The fastest particle is in the second image with a velocity of

788 m/s.
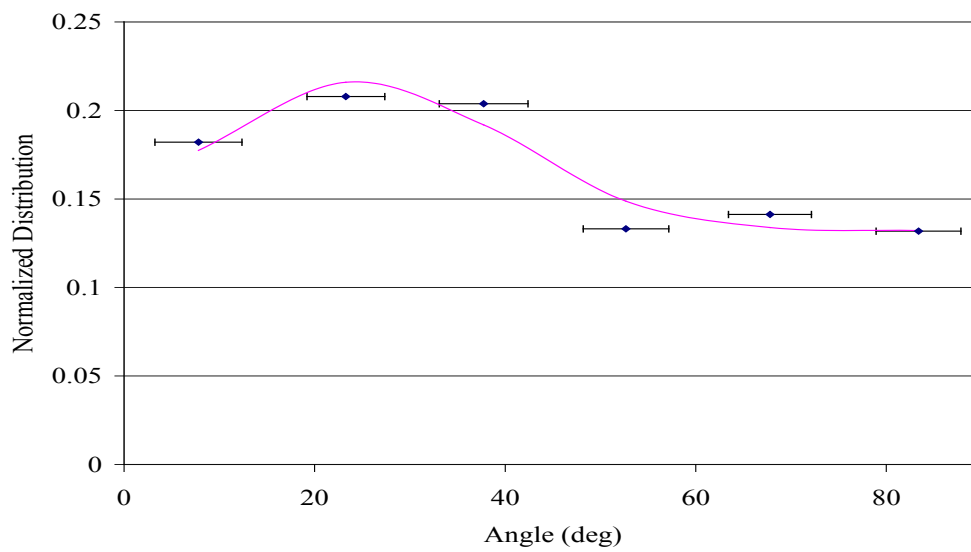
Figure 9: Angular Distribution for Slow Particles, < 300 m/s.

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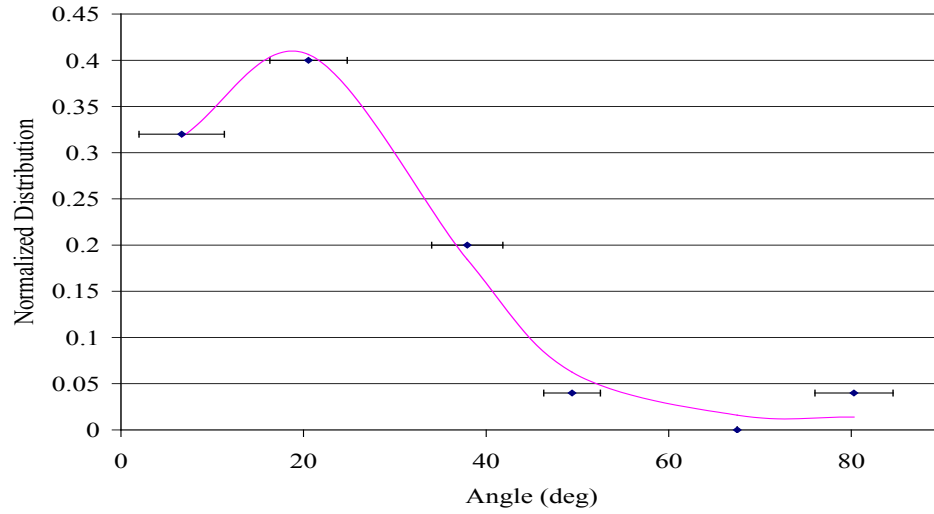
Figure 10: Angular Distribution for Fast Particles, > 500 m/s.
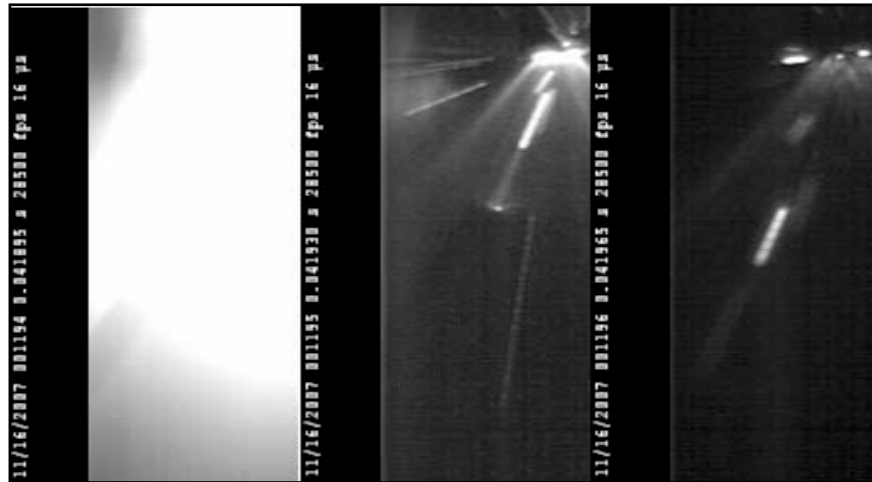
Figure 11: Particle Travel Progress at 28500 fps and 16 μsec of Exposure Time

II.6. **Contamination issue for two-electrode micro-PPT**

Ceylan Kesenek employed a two-electrode micro- PPT for characterizing the

exhaust plume in the vacuum chamber at AFIT (Air Force Institute of Technology).[13]

The experimental setup used witness plates (Figure 12) placed directly in the exhaust

plume in order to capture the mass deposition over a wide angle. The mass deposition on

the witness plates is analyzed using a scanning electron microscope (SEM). The

two-electrode micro-PPTs used in this research were developed at the AFRL Electric

Propulsion Laboratory at Edwards AFB, CA with modifications to the control circuit

developed at AFIT. The DC-DC converter operated over the input voltage range from1

to 15 V and provided up to 7000 V to the thruster. A thruster stand was used to keep the

thruster and witness plates in position. The aluminum witness plates were placed at

several different angles at the same radius from the thruster to characterize the plume

contamination, ensure radial symmetry and as a check on the experimental setup.
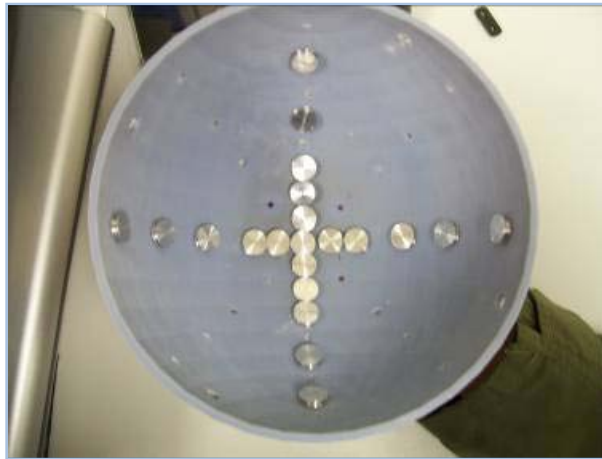
Figure 12: Bowl-shaped Witness Plate Holder

The Scanning Electron Microscope (SEM) was used to examine the witness plates with

up to 133x magnification levels allowing particles with a diameter as small as 5 μm to be

distinguished with sufficient detail. The particles were classified by their diameters

providing a means to determine mass deposition as a function of angle. Cesenek's

research provided four primary results. First, the operation of the micro-PPTs system was

reliable and consistent for up to three hours without any problems. The pulse and pulse

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frequency were well controlled. Table 2 provides two- electrode micro PPT operating conditions used in here.

Table 2: micro-PPT operating condition

Test No	Capacitor Capacitance	Input Voltage (Volts)	Vacuum Pressure (torr)	Duration (Hours)	Frequency (Hz)
1	1 μF	3000	10^{-6}-10^{-7}	1	1
2	1 μF	4000	10^{-6}-10^{-7}	1	0.5
3	1 μF	5000	10^{-6}-10^{-7}	3	0.4

Second, particle diameters ranged from 5 - 60 μm. Some smaller particles were observed at higher SEM magnification but did not considerably contribute to the total mass being deposited. The major contribution of mass deposition is from the 30-50 μm diameter size. Results showed the number of particle with smaller diameters were much more abundant than larger ones. The graph shows more particles exist with diameters less than 30 μm than particles with diameters greater than 30 μm (Figure 13).
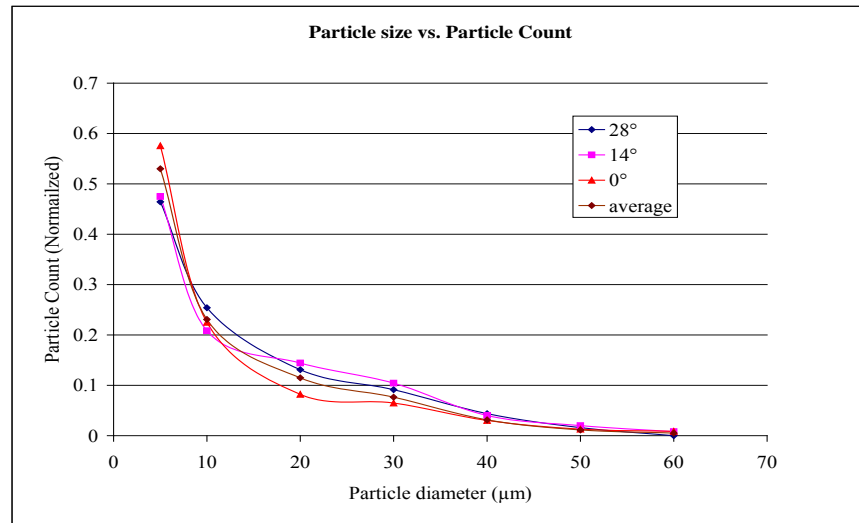
Figure 13: Particle size vs. Normalized Particle Count
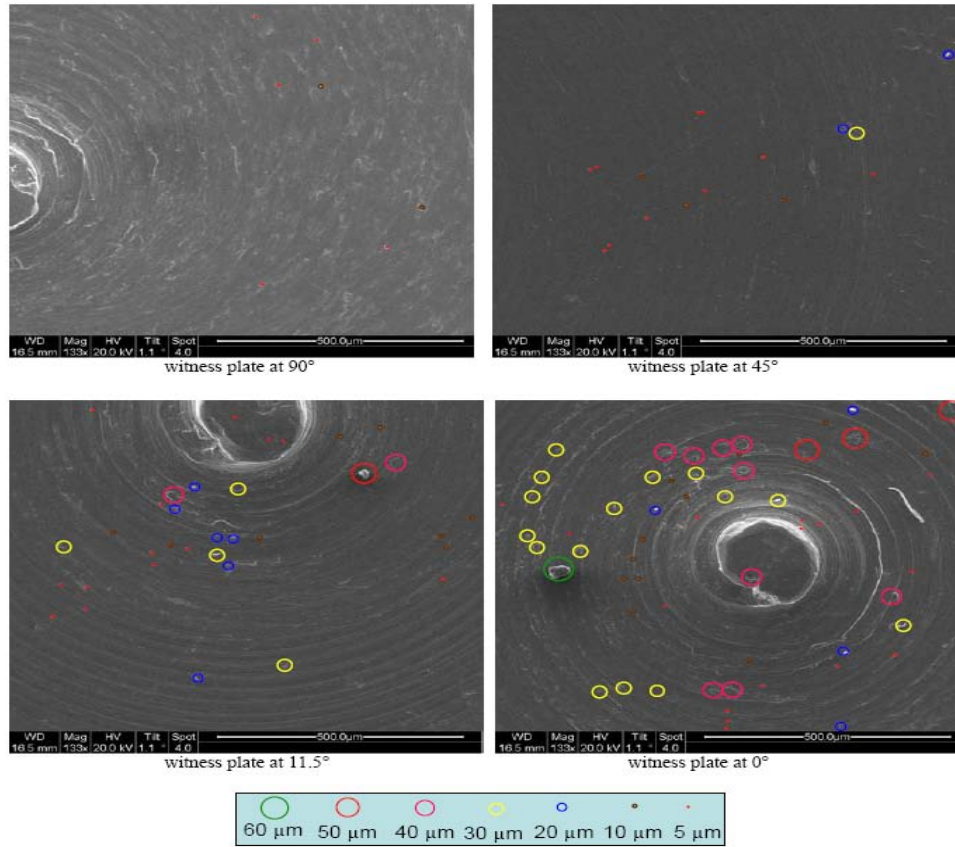
Figure 14: Mass Contribution of Each Particle Size for Various Angular Positions.

The particle size close to the center line tended to be larger (Figure 14). Third, mass deposition profile was created with an average uncertainty of 14%. The mass deposition of the exhaust plume was very high near the axis of the thruster. The majority of mass (93.6 %) was deposited between 0° and 30°. This distribution of the mass can be represented with two distinctly different Gaussian distributions. (Figure 15)
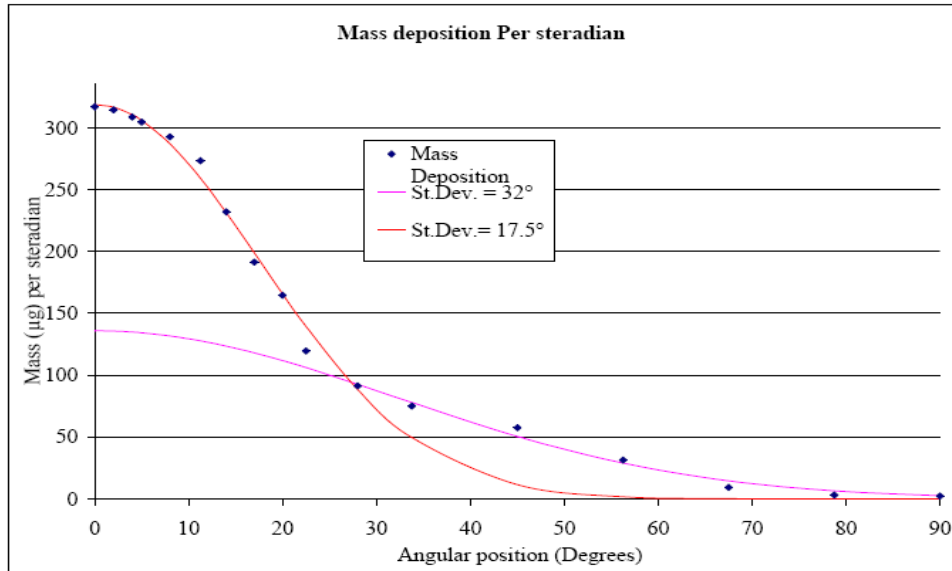
Figure 15: Mass Deposition Profile

Figure 16 shows the mass deposition rates per steradian per pulse versus angular position. When comparing the micro-PPT results here with larger standard PPTs, Kesenek found the mass deposition profile agreed with previous research studies by G. Spanjers, et al, at U.S. AFRL on a much higher powered PPT, 20 J at 1 Hz operation.
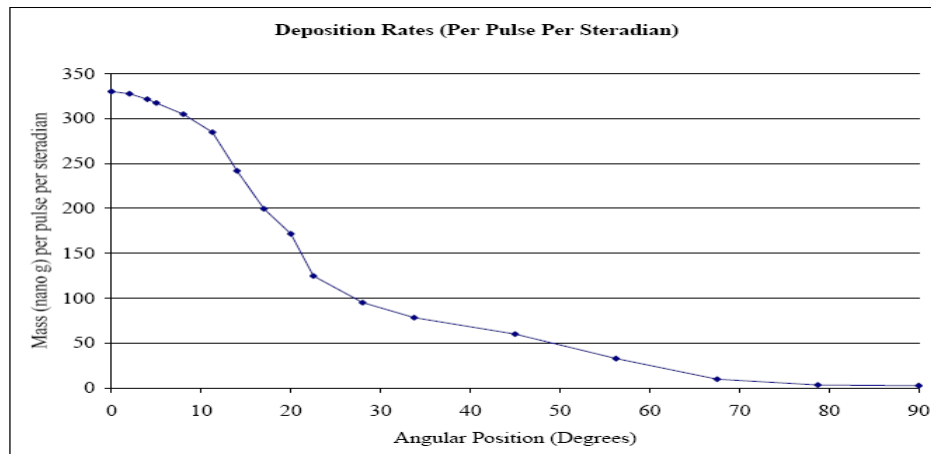
Figure 16: Deposition Rates per Pulse per Steradian

Last, the micro-PPTs were weighted before and after the experiments using a milligram scale with a resolution of 1 mg. The propellant deposited on the surface only accounts for about $4.9 \pm 0.25\%$ of the total mass being ejected from the thrusters. With this information, we can determine the propellant utilization efficiency if we can get information about thrust and particle velocities of the propellant.

III. Methodology

III.1.   Chapter Overview

Experimental apparatus and test setup procedure will be introduced in this chapter. Equipment used in this study includes a vacuum chamber, high-speed cameras, a high voltage pulse generator, a function generator and several electronic components to build the micro-PPT circuit for the three-electrode micro-PPT. This chapter describes the micro PPT circuit, how the particles are captured, and data analysis technique used to evaluate them.

III.2.   Vacuum Chamber

This research was performed in the Geo orbital Nano thruster Analysis and Testing (GNAT) Lab at the Air Force Institute of Technology (AFIT). They have a vacuum chamber manufactured by Laco Technologies capable of pressure as low as 10^{-8} torr. The vacuum chamber can be operated automatically through a LabView 7.0 program. The vacuum chamber is started by double clicking the LabView icon on the computer monitor after turning on power to the vacuum chamber and computer.

Figure 17 shows the LabView screen after the chamber is activated. There are four main menus; runtime, manual control, configuration and shutdown. The run time menu shows the current vacuum chamber state and is used for starting the vacuum chamber. Manual control provides operation of the vacuum chamber manually. The configuration menu can be used to set the various operating values such as crossover pressure, set point pressure and time scale. These two menus do not need to be employed if the vacuum

chamber is working properly. The shutdown menu is then for stopping the vacuum

chamber safely.
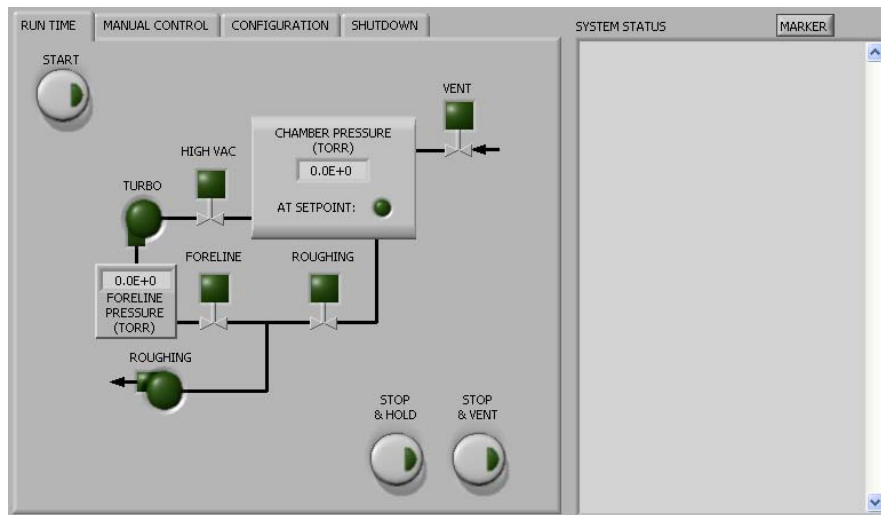
Figure 17: LabView Operation Panel
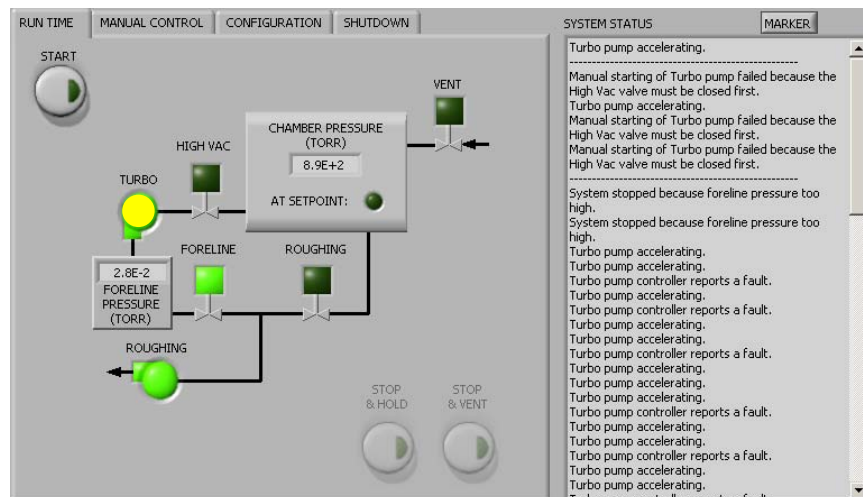
Figure 18: LabView Operation Panel After Activation

Figure 18 shows the LabView screen at startup. The fore line valve opens and the

roughing pump starts the initial evacuation of the turbo pump as indicated by the green

lights. The turbo pump light blinks yellow and green while accelerating to operating

speeds. A green light indicates when the turbo pump is ready (Figure 19); the fore line

pressure drops to the appropriate level.
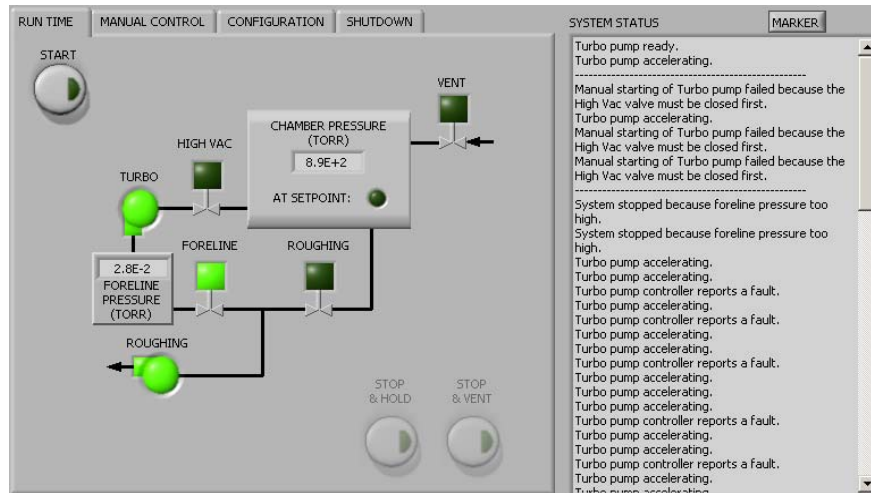
Figure 19: Turbo Pump Ready
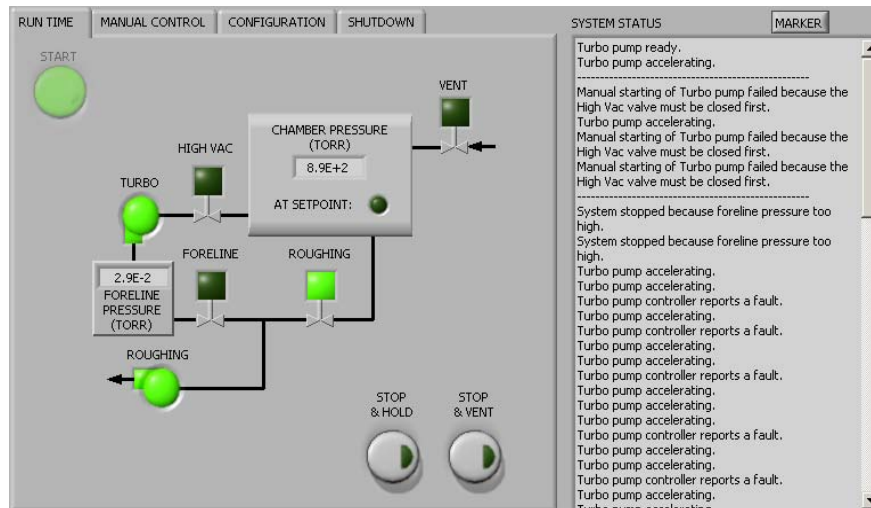
Figure 20: Vacuum Chamber Initial Pump Down Configuration

The fore line valve then closes and the roughing valve opens automatically

(Figure 20). The chamber pressure drops off gradually from atmospheric pressures until it

reaches the crossover pressure set point, 10^{-3} torr. The chamber pressure drops off rapidly

after reaching the crossover pressure and the turbo molecular pump is engaged. At the

crossover, the high vac and fore line valves are opened and the roughing valve closes.

(Figure 21)
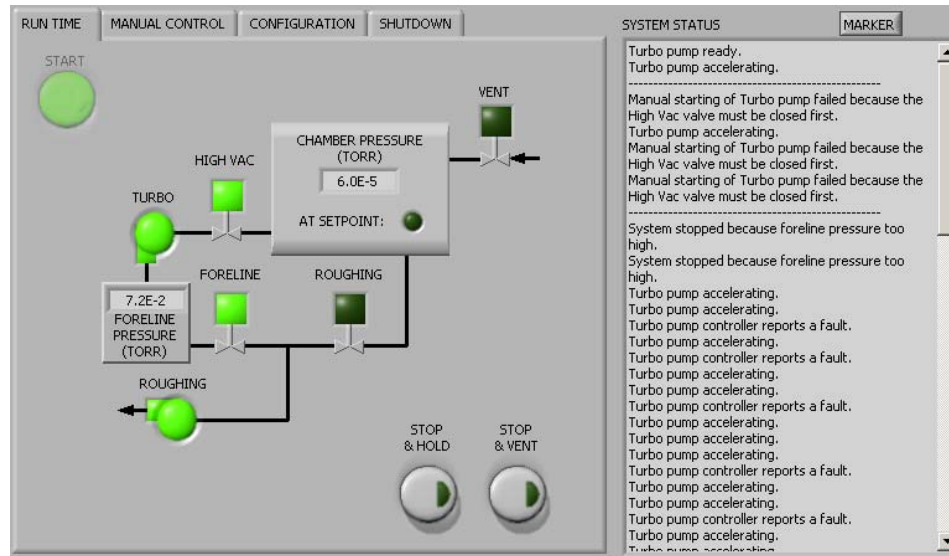
Figure 21: Crossover Pressure Set Point Operation

The research goals and proper thruster operation require simulating a near space

environment. The desired chamber pressure to meet this need is 10^{-5} torr. A blue light

indicates the chamber pressure has reached the desired research environment (Figure 22).

The pressure continues down until the "stop & hold" or "stop & vent" button is hit. The

"stop & hold" button is for stopping the pump and holding the current pressure but the

pressure does start to go up due to leak paths through the pumps. The "stop & vent"

button is for stopping the pump and venting the chamber back to ambient pressure. Both

the high vacuum and roughing valves are closed and fore line valve is open when hitting

the "stop & hold" button. The same occurs for the "stop & vent" with the addition of the

vent valve opening.
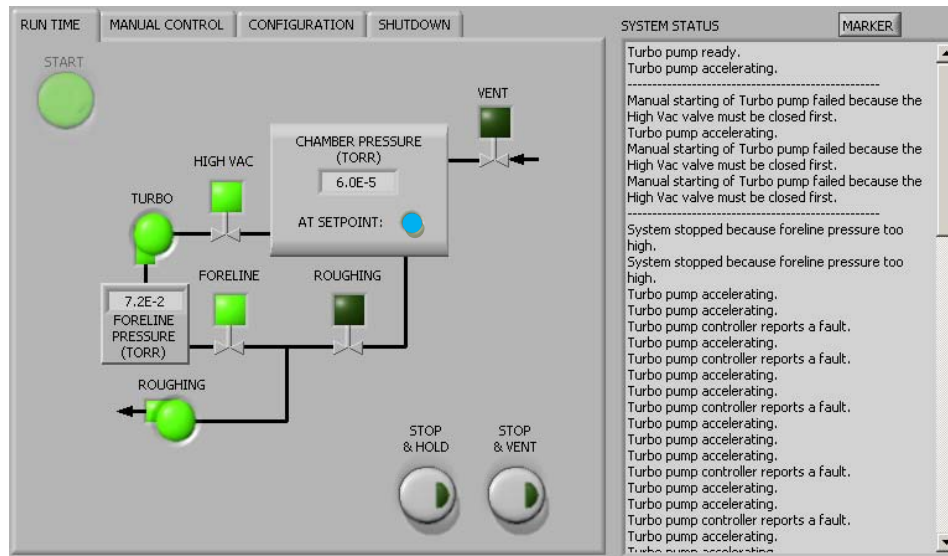
Figure 22: Reaching a Set Point

Figure 23 and Figure 24 show the front and side view of the vacuum chamber

used in this research.

ACT 250

turbo pump
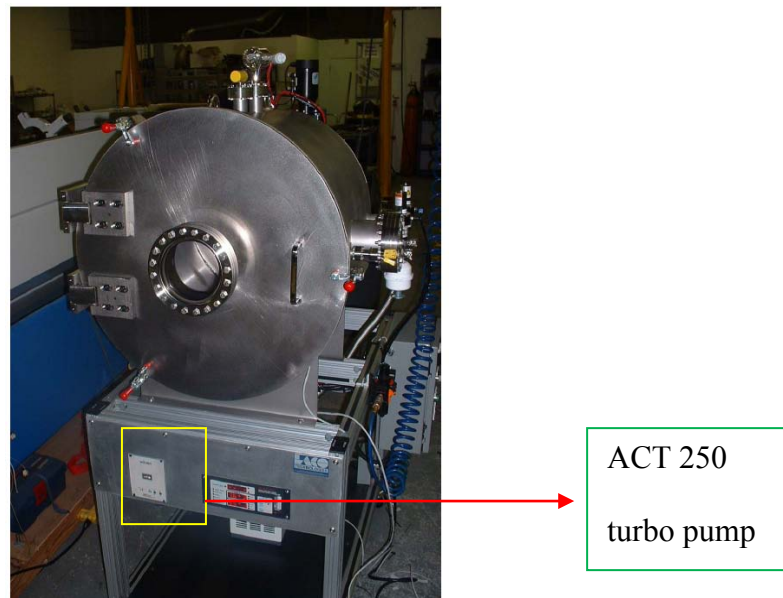
Figure 23 : GNAT Vacuum Chamber #2 Front View
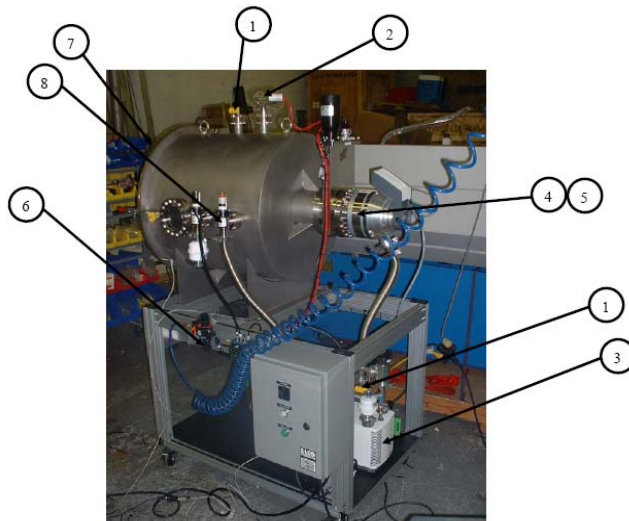
Figure 24: GNAT Vacuum Chamber #2 Back and Side View

Number 3 in Figure 24 is the roughing pump (pumping speed of 27 m^3/h)[14]. This pump can achieve an ultimate pressure without purge of $3x10^{-2}$ mbar ($2.25x10^{-2}$ torr). The turbo pump, (4 and 5 in the figure) provides pumping speeds up to 400 l/s and an ultimate low pressure of $5x10^{-10}$ mbar ($3.75x10^{-10}$ torr)[14]. The ion gauge (2 in Figure 24) measures low pressure using ionization current which decreases with the decrease in the pressure. Figure 25 shows the relationship between pressure and the collector current for the ion gage. This gauge has a linear relationship below 10^{-3} torr. The ion gauge takes responsibility for accurate pressure readings when the chamber pressure drops below 10^{-3} torr.
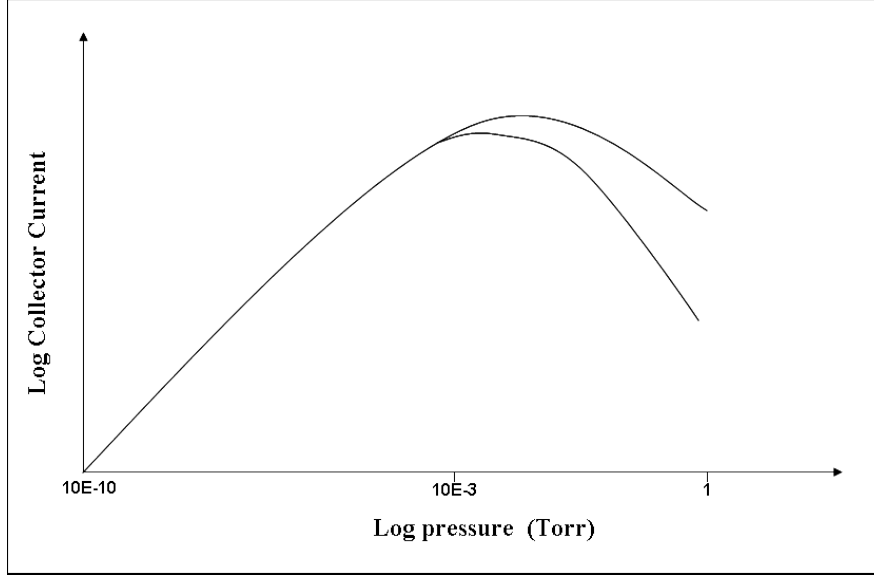
Figure 25: Relationship of Collector Current and Pressure

III.3.　　　**Experimental Setup**

The hi gh speed particles are c aptured with two high-speed cameras from t wo different p erspectives t o qua ntify t he ve locity a nd a ngle i n 3D s pace. In or der t o determine these p erformance pa rameters accurately, assembling t he ne cessary components is c ritical: vacuum c hamber, hi gh-speed cameras, hi gh vol tage pul se generator, f unction ge nerator a nd s ome e lectronic components such as a high vol tage converter, c apacitors and the three-electrode micro-PPT tube. This s ection explains how each component was connected for this test setup. A quick review of each key apparatus will be described as well. Figure 26 shows a schematic of the experiment setup. The HV pulse i s f or s eed i onization, so i t c onnects w ith the intermediate el ectrode and center electrode. The power supply and high voltage converter connect with the outer electrode and center el ectrode for the main di scharge. We us ed two 1.0 μF capacitors to pr ovide enough energy for the main discharge. The three-electrode micro-PPT tube is placed into

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the holder in the vacuum chamber. To determine three dimensional performance, two cameras are placed at specific angles to one another. One is in front of the chamber, the other is placed at 90 degree to the front aimed at the thruster through a side window. The function generator will trigger the HV pulse and the two cameras when triggered giving the images from both cameras capturing the pulse event.
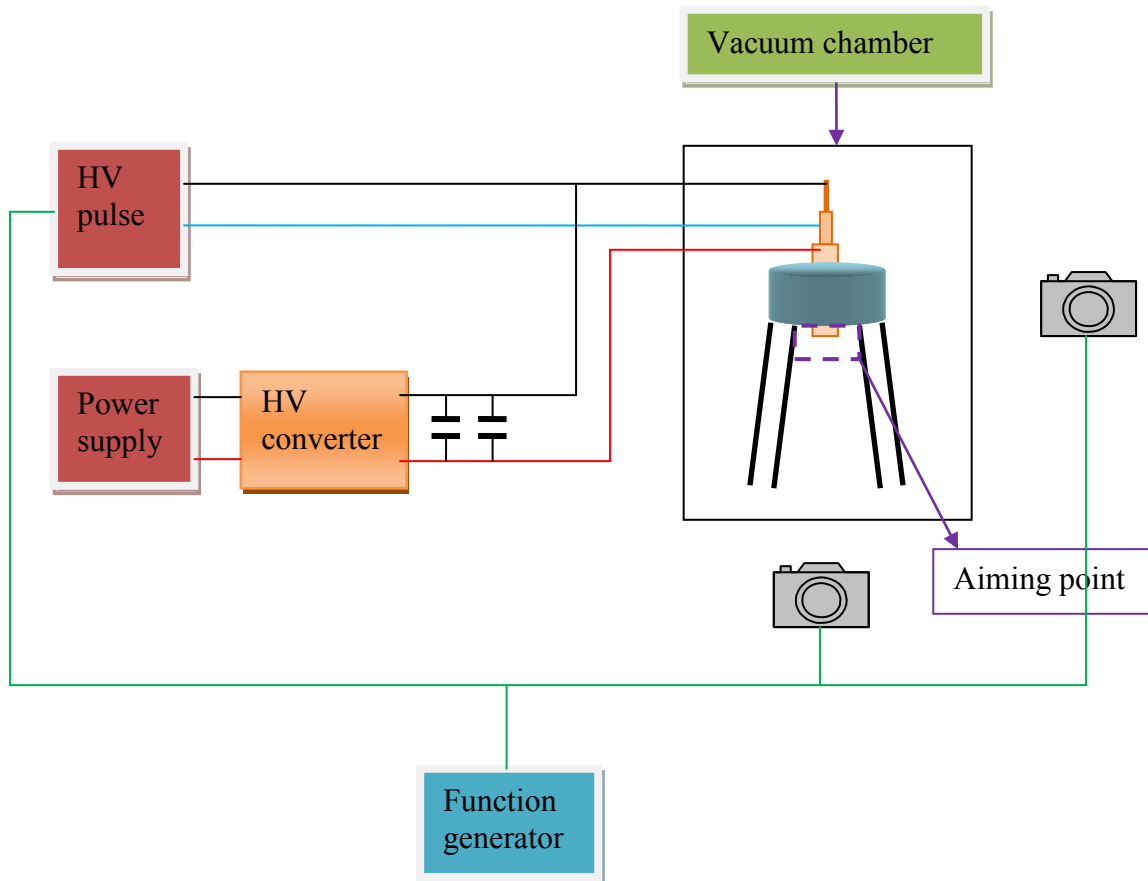
Figure 26: Test setup

The biggest issue in this test setup is synchronization of the equipment. When all equipment is working well and connected properly, the test produced very accurate results. Individually, the equipment such as vacuum chamber, camera and thruster worked well but often proved a bit more temperamental when installed together. One

significant issue was the thruster operation after installed in the vacuum conditions. The high vacuum removed the air normally providing the thruster just enough conductivity across the face to actuate in the lab. Besides the difficulty with getting it to fire, the high voltage lines would often find a short path to ground out to the chamber. Additional care and equipment was needed to ensure high-voltage feed through were properly insulated.

The cameras proved to be sensitive to operation as well. One camera showed an error message when to close to the vacuum chamber, possibly being affected by the high voltage pulse generator. The high voltage affected this specific camera but the second camera (same make and model) did not have this problem. However, the first camera worked well when it was moved farther from the vacuum chamber.

In determining sound operation of the equipment together, settings for the function generator for triggering the intermediate discharge and cameras needed to be varied over a wide range. Finding the right voltage settings to trigger the equipment did not take a lot of time but was essential in providing a smooth operation.

III.3.1. Power Supply

The Agilent E3631A power supply (Figure 27) features a combination of programming capabilities and a linear power supply performance making it ideal for the three-electrode micro-PPT application. The triple power supply delivers 0 to $\pm$ 25 V outputs rated at 0 to 1 A and 0 to +6 V output rated at 0 to 5 A. The $\pm$ 25 V power also provides a tracking output to power operational amplifiers and circuits requiring symmetrically balanced voltages. [15] To supply the DC power to the circuit, the power supply is set to 25 V (#1 and #8 in Figure 27) and then the voltage level is adjusted using

32

the resolution selection key (#10) and control knob (#11). This research explored voltage

input settings from 1 V to 8 V in 1 V increments.
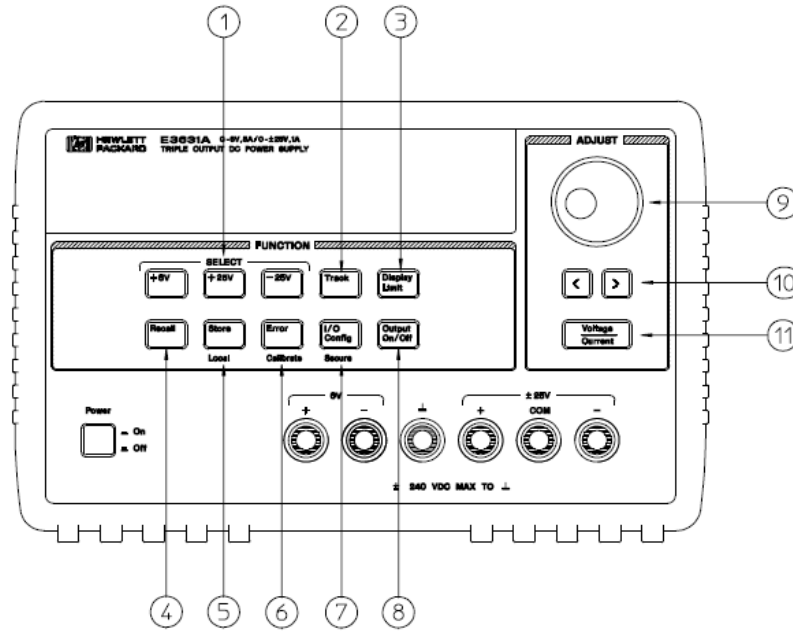
1 Meter and adjust selection keys	6 Error/Calibrate key
2 Tracking enable/disable key	7 I/O Configuration / Secure key
3 Display limit key	8 Output On/Off key
4 Recall operating state key	9 Control knob
5 Store operating state/Local key	10 Resolution selection keys
	11 Voltage/current adjust selection key

Figure 27: Agilent E3631A Triple Output DC Power Supply

III.3.2. High Voltage Converter

The three-electrode PPT uses a high voltage discharge to ablate the propellant.

The EMCO F series (Figure 29) provides 100 VDC to 12,000 VDC (positive or negative

polarity) at 10 Watts continuous output power at an adjustable rate based on input

voltage[16]. Table 3 and Figure 28 show the relationship between power supply and high

voltage converter. The output capability of the pulse generator was measured in the lab to confirm performance and ensure it was capable of providing enough energy to ignite the PPT. This hardware was used from many tests but often did not provide enough energy to the PPT discharge. An alternative circuit was also employed to allow for higher energy discharges.

Table 3 : Relationship between power supply and high voltage converter

Input Voltage	1	2	3	4	5	6	7	8
Output Voltage	290	760	1100	1400	1640	1840	1990	2110
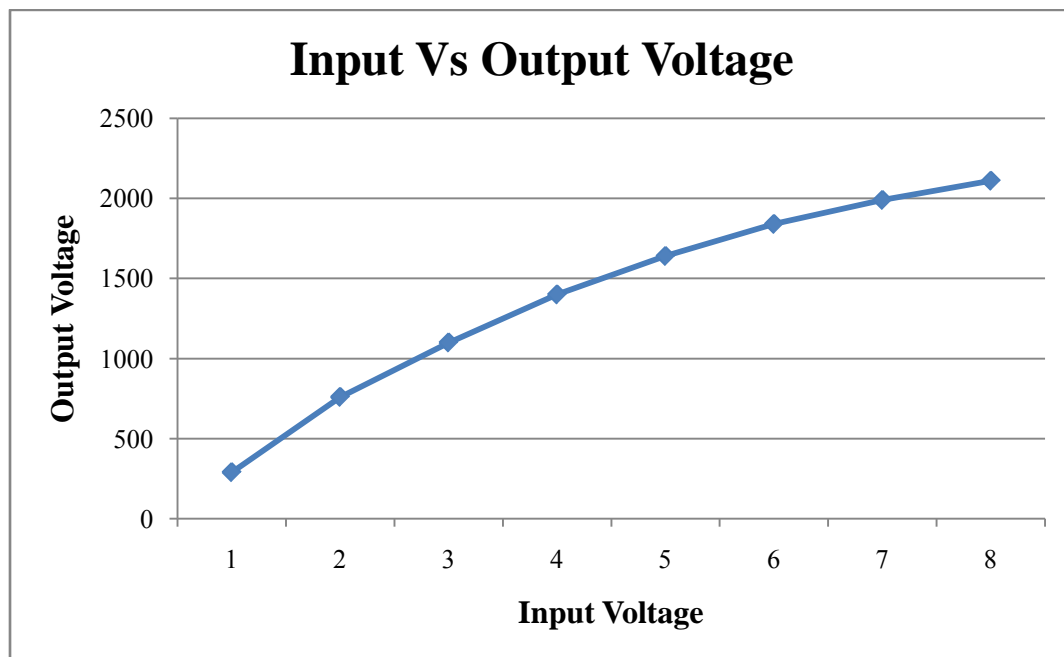
Figure 28: Relationship Between Power Supply and High voltage converter

Figure 29 : Emco Amplifier F series

III.3.3. High Voltage Pulse

To trigger the three-electrode PPT design, a high voltage pulse generator provided enough energy resulting in seed ionization plasma between the inner most two electrodes[17](Figure 30). Table 4 shows some of the specifications for the high voltage pulse. The voltage output, pulse repetition rate and pulse width can all be adjusted to operate at optimal conditions for the test.
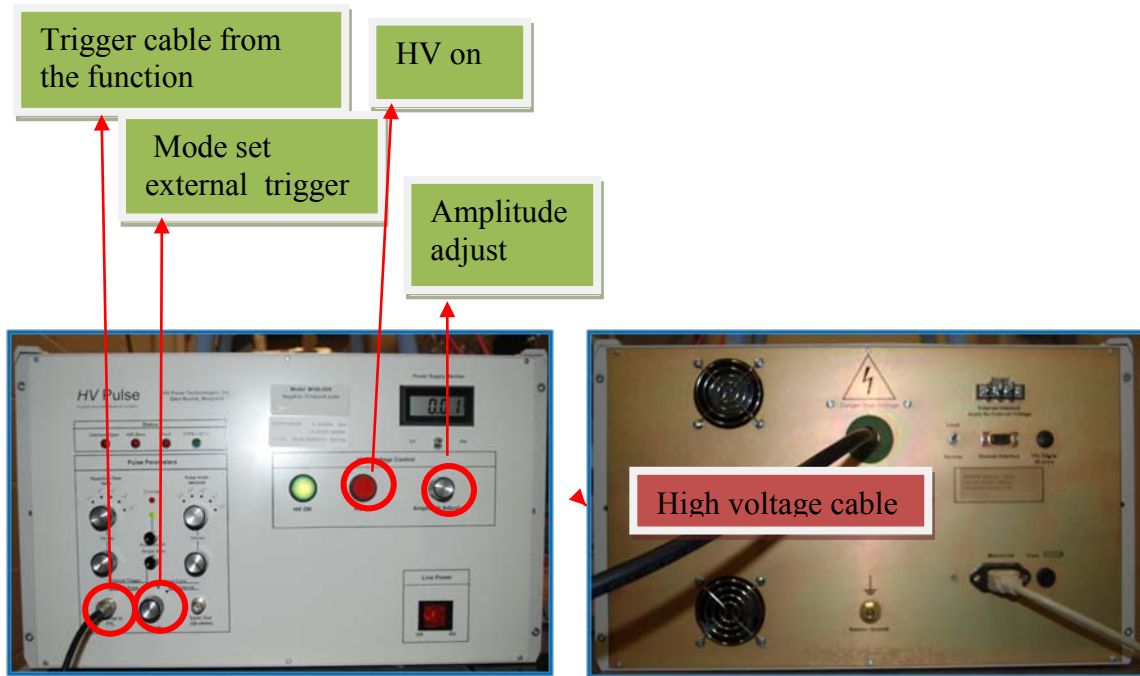
Figure 30: High Voltage Pulse, M10k-20 (Front and Rear View)

Table 4: High Voltage Pulse Generator Specifications

Parameter	External Load	
	None	10,000 Ω / 40 pF
Amplitude (kV)	0.5 to 10	0.5 to 10
Rise Time (ns)	< 150	< 500
Fall Time (μs)	< 5	< 2
Width (50 %) (μs)	3 to 1,000	1 to 100
Max Repetition Rate (Hertz)	> 6,000	> 600
Maximum Duty (%)	> 2	> 0.2

III.3.4. Wave Form Generator, Synchronization

To ensure accurate data capture, the cameras had to be synchronized with each other as well as with the pulse event. The Agilent 33120A is high performance function generator with built in arbitrary waveform capability, suitable for convenient use on a

laboratory workbench and ideal for this test configuration.[18] This function generator can

produce square, sine, triangle and ramp wave forms. The ramp wave proved to be an

effective trigger for the high speed cameras (XS-4) and the voltage pulse generator

(M10k-20) in this research.
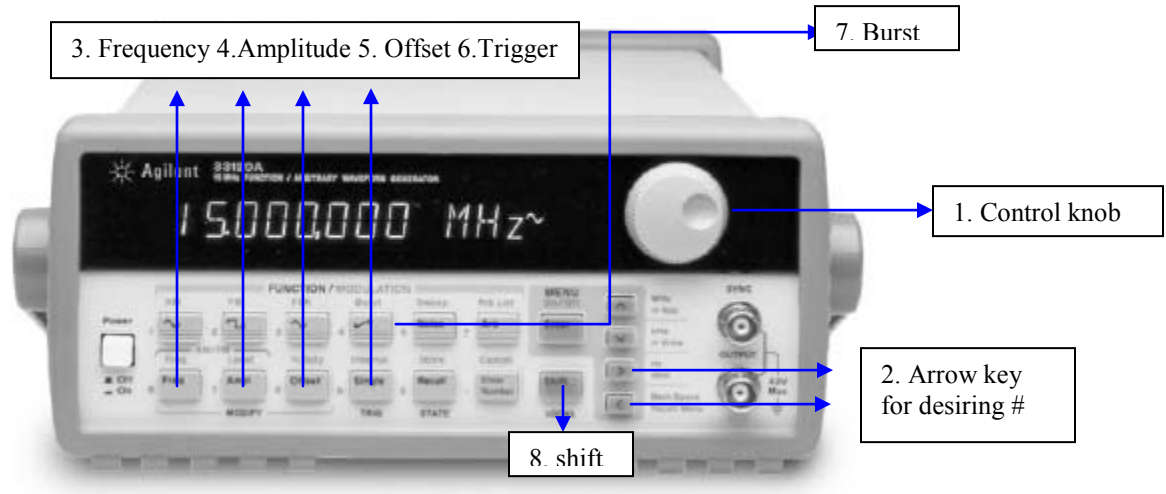
Figure 31: The Agilent 33120A Function Generator

The maximum frequency of the Function Generator depends on the wave form (Table 5).

Output amplitude of the voltage ranges from 100 mV to 20 V. This research sets the

frequency at 1 Hz with 5 V amplitudes. The single trigger is then independent of

frequency. A voltage of only 2.5 V is enough for both the high-speed camera and HV

pulse to trigger.

Table 5 : Output frequency

Wave form	Minimum frequency	Maximum frequency
Sine	100 µHz	15 MHz
Square	100 µHz	15 MHz
Triangle	100 µHz	100 kHz
Ramp	100 µHz	100 kHz
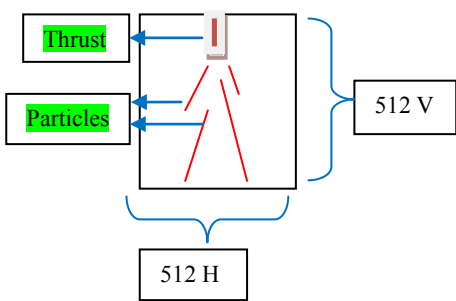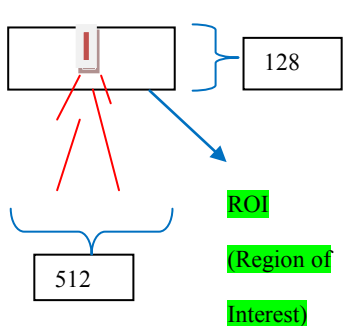
III.3.5. High Speed Cameras

The Motion Pro XS-4 camera features a USB 2.0 (480 Mbps) digital interface and Giga Ethernet (1000 Mbps) providing high-speed rate of transfer to a desktop or laptop computer with a single cable. The camera captures the motion of objects at ultra-high speeds.[19] It has 4 GB internal memory and provides maximum resolution of 512 H x 512 V. At the full resolution (512x512 pixels), the camera can capture images as fast as 5,145 frame per second (fps). The frame rate is important in this research because particle speeds are on the order of 500 to 1000 m/s. The frame rate can be increased by reducing the image resolution. Table 6 shows the relationship between image resolution and maximum frame rate. The camera trades increased frame rate with vertical pixel size providing a means to capture axially traveling particles at good resolution in the primary axis of travel while increasing the frame rate capture. The first row figures in Figure 32 shows the vertical pixel reduced from 512 to 128 keeping the horizontal pixel value the same increasing frame rates by about 4 times more. Properly orienting the camera can improve data capture in the region of interest (ROI). If the camera is aligned vertically with the thruster, reducing the vertical pixels to capture high-speed particles results in not capturing useful information. The vertical image region is too narrow. Most of particles

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exit the ROI as shown in the third figure in the first row of Figure 32. This is why the cameras were aligned horizontally. The second row of figures in Figure 32 shows the ROI capturing high-speed particles more effectively. The specification of XS-4 camera is shown in Table 7.

Table 6: Relationship Between Image Resolution and Max Frame rate[20]

Image Resolution (pixels)	Max Frame Rate (Hz)
512H x 512V	5,145
512H x 256V	10,241
512H x 128V	20,288
512H x 64V	39,822
512H x 32V	76,790
512H x 16V	143,307
512H x 8V	252,794
512H x 4V	409,053

Camera Set	Camera appearance	Image appearance at full resolution 512 H x 512 V (5145 fps)	Image appearance at 512 H x 128 V (20,288 fps)
Original set			

90 degrees turned set		512 V 512	128 V 512 H
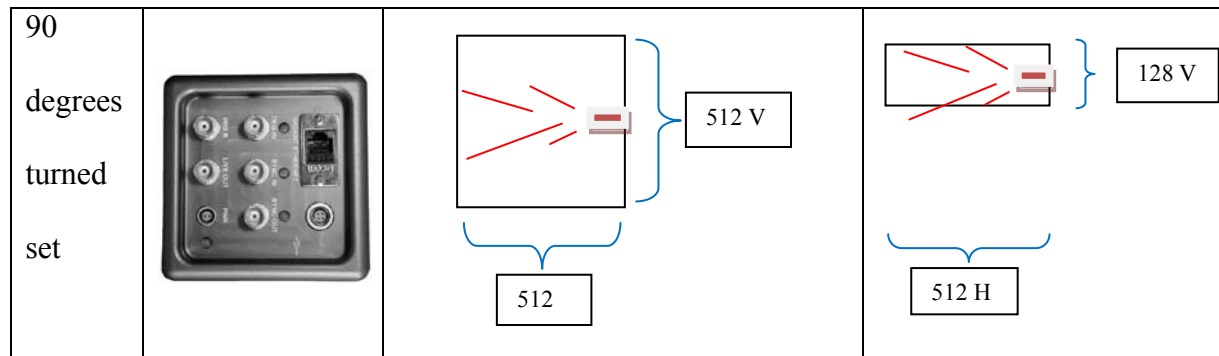
Figure 32: Comparison Between Original and 90 Degrees Turned Camera Set

Table 7 : XS-4 Camera Specification[20]

Pixel Depth	10 bits
Resolution	512 H x 512 V pixels
Pixel Size	16μ x 16 μ
Center to Center Spacing	16 μ
Pixel Fill Factor	40 %
Dynamic Range	59 dB
Trigger Mode	Integral (continuous), external (edge-low, edge-high, pulse low and pulse high)
Minimum Inter-frame Rate	100 ns
Trigger and Synchronization	CMOS level (3.3 V) via BNC connection
Digital interface	USB (480 Mbps), Giga Ethernet (1000 Mbps)

The cameras were triggered and therefore connected differently than in previous research. Using sync in and sync out on one camera setting it as master and the other camera as slave proved problematic and did not trigger properly. In this configuration, only the master camera was able to take the image. Therefore, each camera was connected directly to the function generator and triggered simultaneously. The power

lines and USB cables are connected to each camera as well to complete the data transfer

from the cameras to the computer (Figure 33). Camera operating procedures for this

research are explained in detail in Appendix A.

.
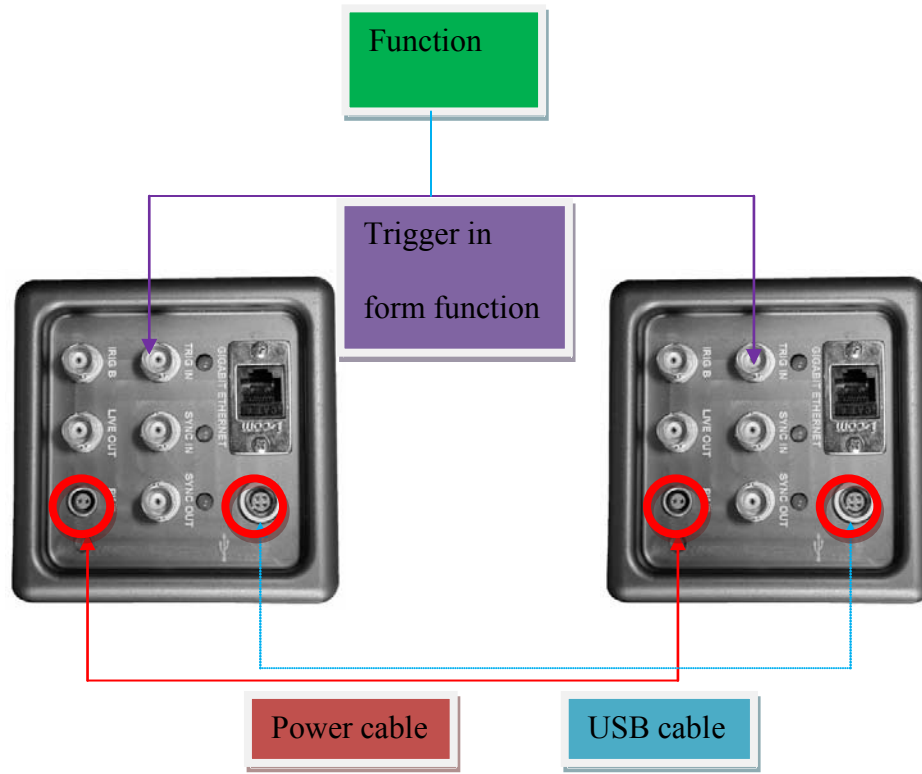
Figure 33: Cable Connection to High-Speed Camera

The lens used in this test was an AF Micro-NIKKOR 60mm f/2.8D which has a

60 mm focal length and the aperture scale is f/2.8 (maximum) to f/32 (minimum)(Figure

34).

Figure 34: AF Micro-NIKKOR 60mm f/2.8D Lens

III.3.6. Three-Electrode micro-PPT Tube

The micro PPT tube used in this research is a 3.175 mm (1/8"), three-electrode design. Figure 35 shows the three-electrode micro-PPT tube geometry. The three-electrode design has two inner electrodes with a much smaller spacing than the main outer electrode. We have already described the two and three-electrode micro-PPT designs in chapter 2 with Figure 2 and Figure 3. Three-electrode micro-PPT has three main benefits when comparing to two-electrode designs. The three-electrode micro-PPT has minimal shot to shot variation decreasing the possibility of carbonization on the propellant face and requires less voltage potential to initiate the main discharge, relying on seed ionization from the intermediate discharge. It can also control the firing frequency easily by simply increasing or decreasing the operation frequency of the input power. However it has more complex circuitry than the two-electrode designs as shown in Figure 3.
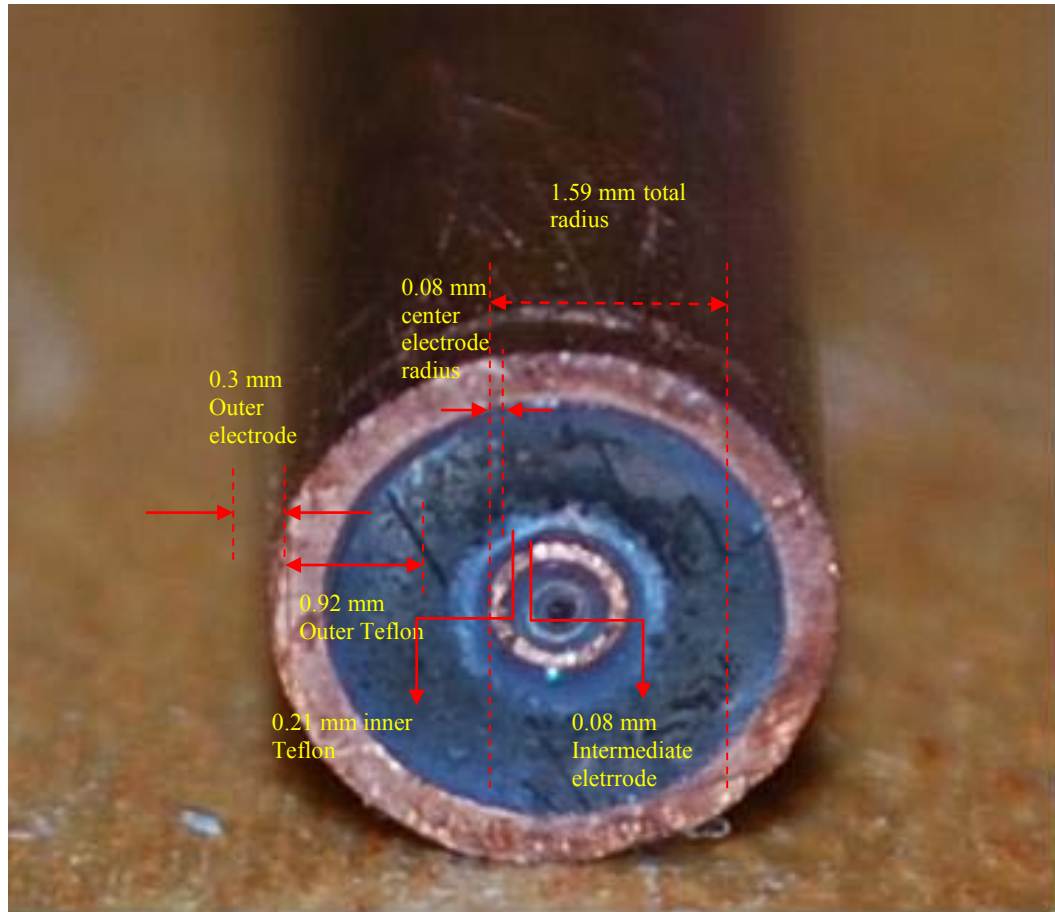
Figure 35 : 3.175 mm (Diameter) Three-electrode micro-PPT Tube

Operating conditions for this geometry can be determined directly. Assuming 10^4 amps current and the PPT can theoretically produce 10,000 m/s exhaust velocity in the ionized gas (as found from previous research), capacitance falls in the range of 0.32 to 1.6 µF using the equation $C = Q_0/V_0 > 0.0016/V_0$ for a voltages in the range of 1,000 to 5,000 V. The time scale for a micro-PPT is on the order of 1.59 x 10^{-7} for the two electrode micro-PPT test. The initial charge storage of $Q_0 \approx J\tau > 0.0016$ coulomb is required to sustain the pulse through the discharge. Using these operating conditions, the discharge energy was as high as 6.5 joules according to equation;

$$W = \frac{1}{2}CV^2 \tag{2}$$

Where, V is 3,600 V of surface breakdown voltage and C is a 1 µF capacitor12. In this research, input voltages ranged from 4 to 8 V. The corresponding discharge energy was 2 joule at 1400 V (4V input) and 4.5 joule at 2110 V (8V input) (Figure 36, showing the circuit consists of high voltage converter and two 1µF capacitors).

Figure 36 : Circuit using two 1µF Capacitors Connected and High Voltage Converter

III.4. **Data Evaluation Method**

The start and end coordinates of each particle streak were measured using image software to determine the length of streak for each particle. After measuring the pixel numbers of the particle streak in the picture, the results were converted from pixel length

to physical length. The procedure to determine the physical scale for a single pixel

involved two independent methods to increase fidelity in the measured value. One way is

simply using a ruler placed in the focal plane at the PPT. The other is using the PPT tube

diameter as a reference, converting the known dimension into pixels. For this

configuration, the ruler showed 59 mm corresponds to 512 pixels (Figure 37), resulting in

one pixel equating to 0.115 mm. With this information and the image exposure time, the

velocity of the particles can then be calculated. As an example, the velocity of a particle

moving through 256 pixels corresponds to 29.5 mm. If the exposure time is set at 30 μsec,

the velocity is 983 m/s.
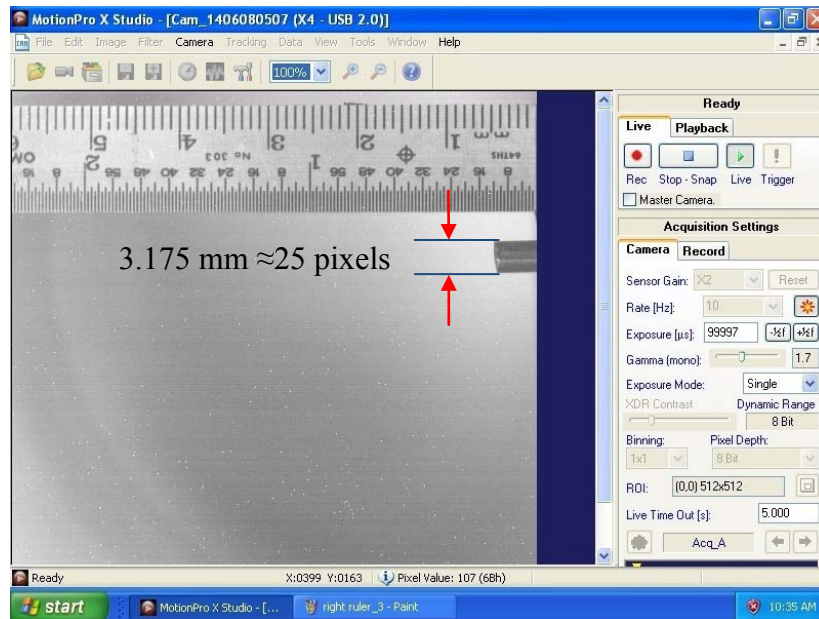
Figure 37 : Measuring the Physical Length Scale

The PPT tube measured about 25 pixels across. The physical diameter of the tube

is 3.175 mm giving a one pixel dimension of 0.127 mm. There difference in the two

methods resulted from a distance change from the camera to the PPT between

experimental events. Knowing the changes in the actual location of the cameras allows us to correct for any variations due to pixel/length changes. Added to this potential systemic error, using the tube diameter had to be carefully handled. The light around the outer electrode often saturated many pixels and could cause erroneous measurements of the number of pixels in one diameter. The variations of the physical pixel scale from test to test were captured and applied appropriately to ensure no unnecessary error was introduced into the final results. With this precaution, introduced error due to pixel resolution can then be quantified. Table 8 shows the average tube cross distance (pixel) and one pixel error (m/s) for each exposure time. All particles have less than a possible variance of 10 m/s for one pixel except 10 μsec case which account for 1.2% of total particles.

Table 8 : One pixel error (m/s) in each exposure time

Frame rate	exp. time	# of particl es	average X length of tube (pixel)	average Y length of tube (pixel)	x_z plane one pixel error (m/s)	y_z plane one pixel error (m/s)	Percentage # of particles
	20	121	22.6	22.9	7	6.9	2.4
14100	30	494	22.6	22.9	4.7	4.6	9.9
	40	118	22.6	22.9	3.5	3.5	2.4
Subtotal		733					14.7
	10	62	23.9	24.6	13.3	12.9	1.2
	20	100	23.9	24.6	6.6	6.5	2
24500	30	21	23.9	24.6	4.4	4.3	0.4
	37	97	23.9	24.6	3.6	3.5	1.9
Subtotal		280					5.6
	14	98	25.6	25	8.9	9.1	2
	20	157	25.6	25	6.2	6.4	3.1
	24	622	25.6	25	5.2	5.3	12.5
	25	309	25.6	25	5	5.1	6.2
26500	30	1925	25.6	25	4.1	4.2	38.6
	34	583	25.6	25	3.6	3.7	11.7
Subtotal		3694					74

31500	28	95	-	-	-	-	1.9
50502	16	189	23.3	24.7	8.5	8	3.8
Total		4991					100

III.4.1. Determining 3D Velocities

Converting the 2D images into 3D velocities requires identifying the same particles in the two different images. In the following image, a red particle trace shows how a particle moving away from the thruster will be captured by each of the cameras. The front and side cameras will capture the image shown by the orange lines. If we use representative lengths as shown in Figure 38 for an example, the length of the particle path in the front camera image is $\sqrt{3^2 + 5^2}$ and the right side camera image is $\sqrt{2^2 + 5^2}$. The actual path taken by the particle (red streak) length will be $\sqrt{3^2 + 2^2 + 5^2}$. The images from the front and side cameras will have the same vertical length if the two cameras have same exposure times. With the use of some vector math, the velocities of all distinguishable particles can then be determined by simply dividing the path length by the exposure time. The total number of particles captured from each camera was 4991 for all operational conditions, approximately 1000 particles for each power setting.
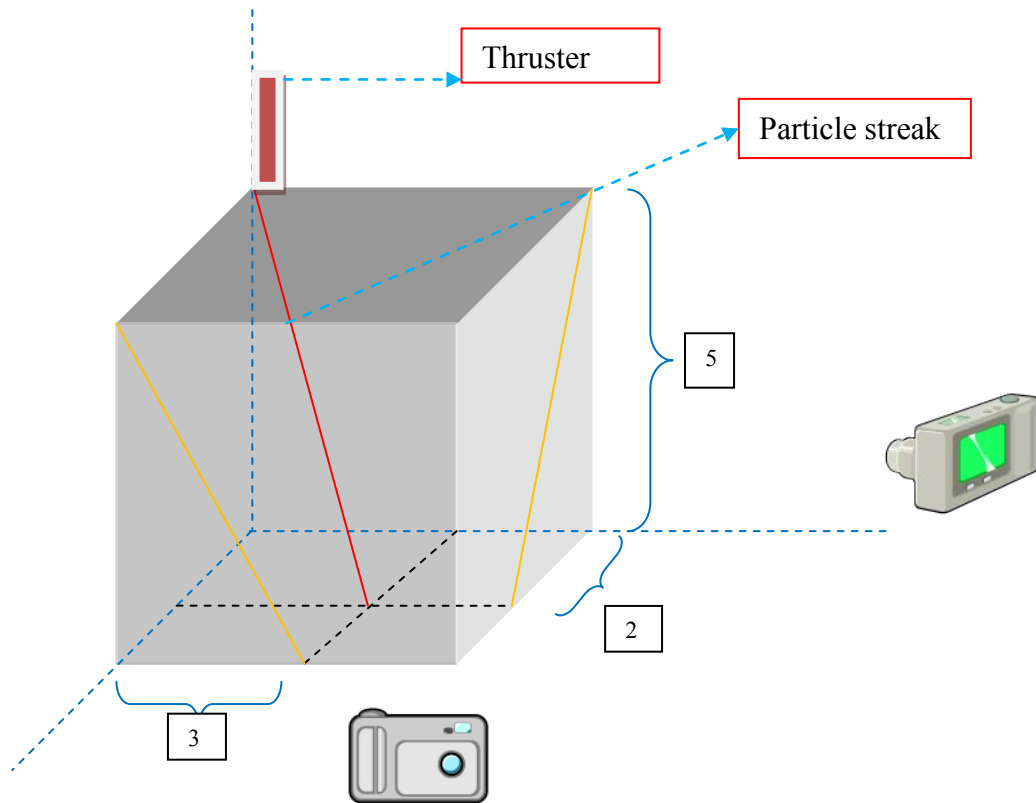
Figure 38: Measuring the Particle Streak Length

IV. Analysis and Results

IV.1.   **Chapter Overview**

The operating range for a reliable three-electrode micro-PPT was tested. Particle data

from each camera varying the energy level was analyzed for velocity and angle

distribution. The velocity and angle distribution for each energy level was compared to

find out the effect of energy on the velocity and angle distribution. Thruster performance

(I_{sp}) for each energy level is determined from this result showing which operation results

in the highest contribution to I_{sp}. Error corrections for accurate data are included in this

discussion.

IV.2.   **Operating Energy Range for the Three-electrode micro-PPT**

The HV pulse generator (Model name: M10k-20) provided the intermediate discharge

energy for three-electrode micro-PPT primarily because it only contributes 0.002 Joule to

the operation of the thruster but can be easily controlled (8,000 V output volt and 50 pF

capacitor). The main discharge energy level ranged from 0.1 Joule (1V input voltage) to

4.5 Joule (8 V input voltage) for operating the three-electrode micro-PPT. The micro-PPT

did not function at the lowest energy levels from 0.1 Joule to 0.6 Joule in spite of the

consistent delivery of the seed ionization from the HV pulse generator. It simply emitted

a small spark from intermediate discharge. At 1.2 Joule (3 V input voltage), the micro-

PPT fired with a blue light but ejected particles were not evident because the supplied

energy was insufficient to produce particles and potentially enough thrust-producing

plasma to be useful. Particles were captured with the cameras over the energy range from

2 Joule to 4.5 Joule. The thruster was exercised over 1,000 times for each energy level without any problem when triggered from the function generator. The maximum input voltage employed was 8 V, 2,110 V output volts (4.5 Joule equivalent energy). Since the current power supply is limited to an input voltage of just 10.0 V. Additionally, there exists some danger to the electronic circuit above 8 V. One high-voltage converter was destroyed when operated at the highest voltage of our power supply.

Table 9 : Three-electrode micro-PPT Operability Test Results

Input (V)	1	2	3	4	5	6	7	8
Output (V)	290	760	1100	1400	1640	1840	1990	2110
Energy (Joule)	0.1	0.6	1.2	2	2.7	3.4	4	4.5
Work or not	Not	Not	Work but weak	Work	Work	Work	Work	Work

It was also noticed firing the thruster was easier in the atmosphere rather than at vacuum conditions. The thruster failed to fire at vacuum conditions on several occasions even though it worked at atmosphere with the same energy. For example, the two-electrode micro-PPT worked weakly using the HV pulse generator (0.002 Joule) in atmosphere but it did not work in the vacuum chamber at pressures below 10^{-5} torr causing significant delay in capturing the data.

IV.3.   **Captured Particles**

Table 10 shows the particle numbers captured by each camera at the different operating conditions such as energy, camera frame rate and exposure time. The pictures were taken with frame rates ranging from 14,100 to 50,502 fps and exposure time range from 10 to 40 μsec but the bulk of the data was taken at 26,500 fps (74%) and 20 to 30

μsec exposure time (77 %) as shown in Table 11. The number of total particles captured

for each camera was 4991, approximately 1,000 particles at each energy level with

various frame rates and exposure times.

Table 10 : Summary of Captured Particles

Main Discharge Voltage (V)		Energy (J)	Camera Frame Rate (fps)	Camera Exposure Time (μs)	Number of Particles
Power Supply (V)	Voltage (V)				
4	1400	2	26500	24	295
			26500	30	494
			26500	34	205
Subtotal					994
5	1640	2.7	26500	20	157
			26500	25	218
			26500	30	639
Subtotal					1014
6	1840	3.4	24500	10	62
			50502	16	189
			14100	20	121
			24500	20	100
			14100	30	294
			24500	30	21
			24500	37	97
			26500	30	117
Subtotal					1001
7	1990	4	14100	30	200
			14100	40	118
			26500	25	91
			26500	34	61
			31500	28	95
			26500	30	450

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Subtotal					1015
8	2110	4.5	26500	14	98
			26500	24	327
			26500	34	317
			26500	30	225
Subtotal					967
Total					4991

Table 11: Captured Particles Sorted by Frame Rate and Exposure Time

Frame Rate (fps)	Number of Particles	Exposure Time (μs)	Number of Particles
14100	733	10	62
24500	280	14	98
26500	3694	16	189
31500	95	20	378
50502	189	24	622
		25	309
		28	95
		30	2440
		34	583
		37	97
Total	4991	40	118
		Total	4991

The exposure time and frame rate were varied to ensure faster particles were being captured. The higher frame rate reduces the pixel resolution size and is therefore not always the best setting for capturing distinguishable particles. The distinguishable particles are easiest to distinguish just after the spark event. The spark duration can be found from the time setting (using frequency setting) of the HV pulse generator, which

provides a seed ionization.. Figure 39 shows three consecutive pictures starting with a firing of the PPT. In the first frame the only thing visible is the light from the spark event. The streaks are then captured in the second frame of the X_Z plane. If the camera was set at a higher frame rate (for example, 20,000 fps which has 50 μsec duration between frames), then some streaks (#1 in the second frame) may not be captured, (frame rate time interval is 31 μsec in this case).

Another problem was capturing the particles with both cameras, Figure 39 and Figure 40. There are two reasons why particles would be missed by one or the other camera. First, a time difference between the two cameras in actually capturing images, although the same second frame should coincide due to the trigger, Figure 39. A sign indicating the particles were not taken at the same time is the light in the second frame. The second frame in X_Z plane appears later in time past the firing than the Y_Z plane. The second introduced error in capturing the same particles with the two different cameras is different focusing planes for each camera, even when there is no time difference between the cameras. Particles often have a shallow angle to the thruster centerline in one plane (for example, X_Z plane) but have a steeper angle in the other plane (for example, Y_Z plane) or vice versa. For instance, Particles #2 and #3 in the second frame in Y_Z plane cannot be found in the second frame in the X_Z plane in Figure 40.

	X_Z plane	Y_Z plane
1st fame		
2nd frame	71 µsec X Z 1 40 µsec	Y Z
3rd frme	31 usec	
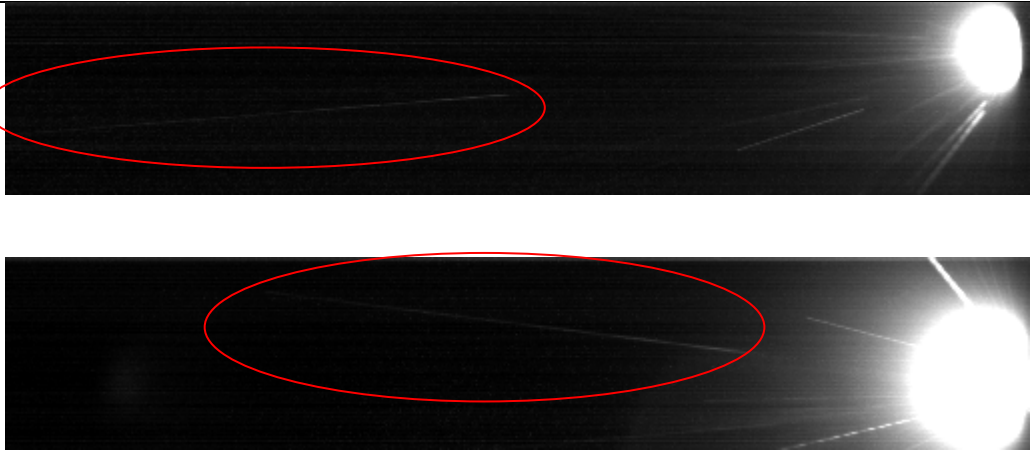
Figure 39: Three Consecutive Frame at 14,100 fps 40 µsec

	1st frame	2nd frame
X_Z plane	1	2
Y_Z plane	1	2 & 3

Figure 40 : Different Focusing Plane (8V 26,500 fps 30 µsec)

Figure 41 shows fast particles captured by both cameras for each energy level. To determine three-dimensional velocity, the particles must be captured by both cameras.

There is a time difference between the two cameras in many cases, Figure 41. However, we can determine the same particles in the different images by simply comparing the axial length. For images at the same exposure time, the axial length will be the same for the particles taken at different positions. This is the method described in the 3D velocity evaluation methods in chapter 3.

Condition & Velocity	Image : X_Z plane & Y_Z plane
4V 26500fps 30 μsec 1001 m/s	
5V 26500fps 20 μsec 774m/s	
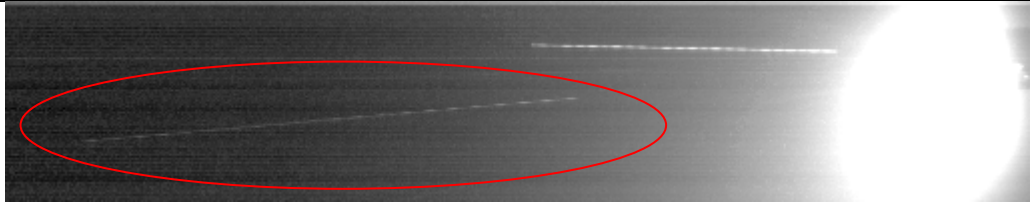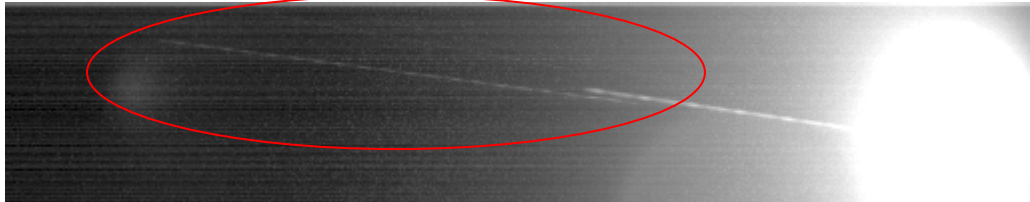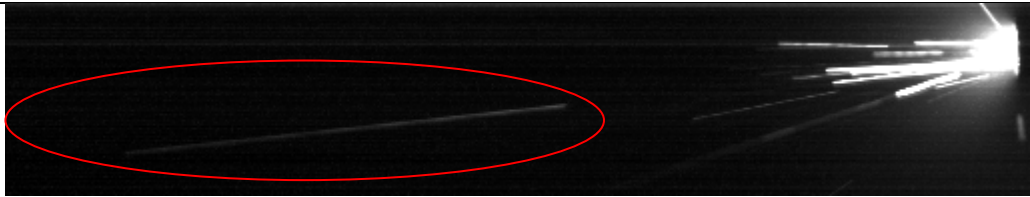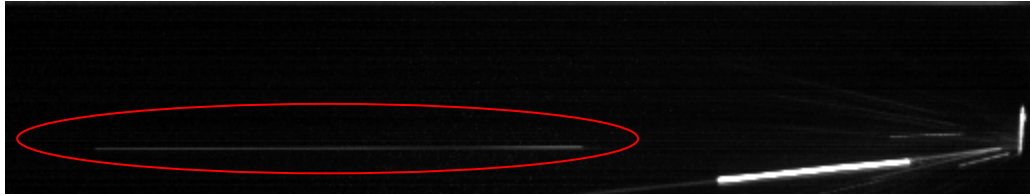
6V 24500fps 30 µsec 1029 m/s	
7V 26500fps 30 µsec 921 m/s	
8V 26500fps 34 µsec 940 m/s	

Figure 41 : Fast Particles at Each Operating Condition.

Also, some cases had very fast particles that could not be distinguished due to the number

of particles captured by one camera as shown in Figure 42.

8V 26500fps 34 µsec	
8V 26500fps 24 µsec	
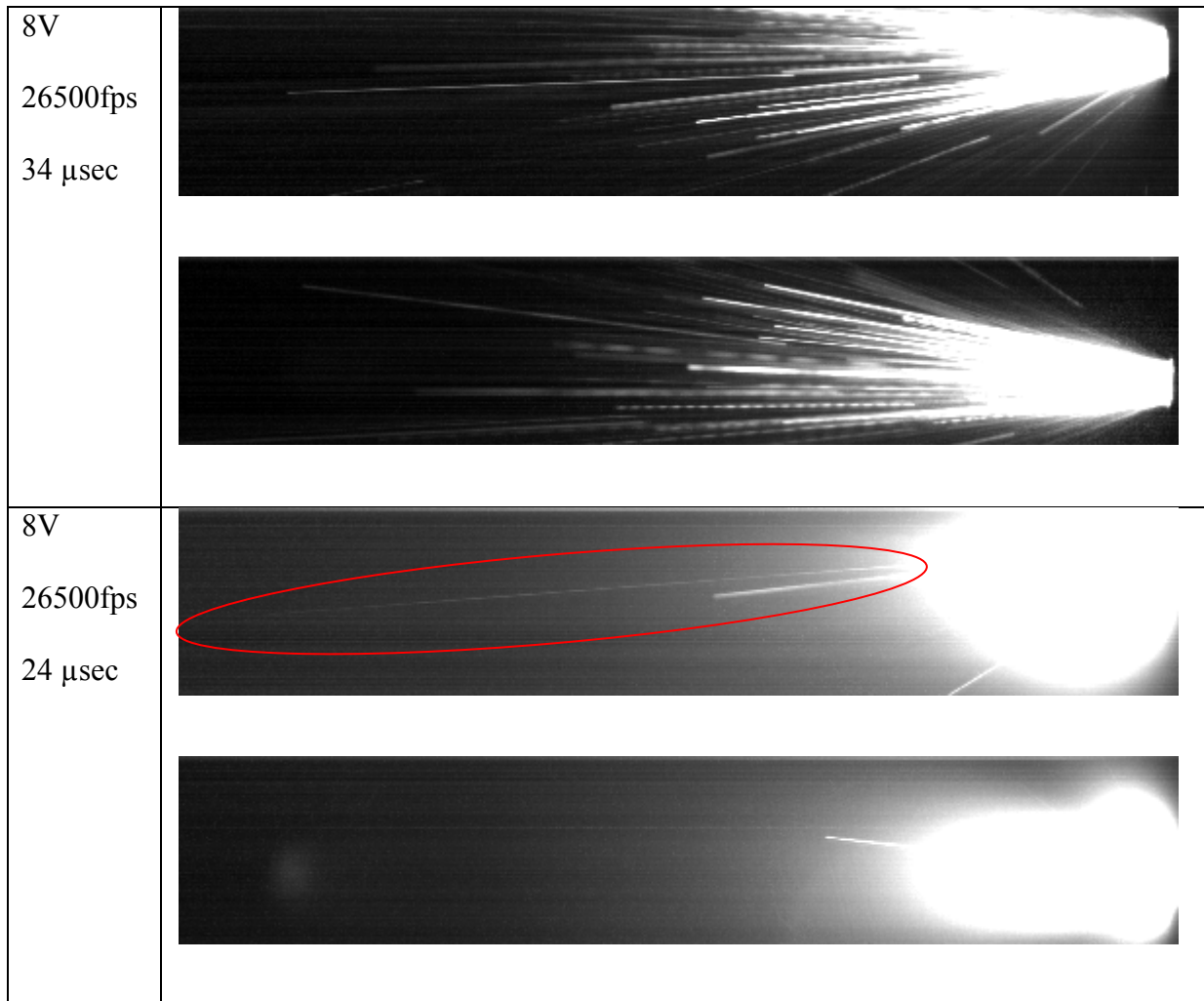
Figure 42: Fast Particles

IV.4.   **Angle Error Correction for Tilted Thruster**

The thruster axis was tilted a slightly (2 - 3 °) from the picture axis. The thruster axis

in the X_Z plane was tilted to the right and the thruster axis in Y_Z plane was tilted to the

left from the picture axis when looking at the pictures with the thruster at the top of the

image. The sign of the angle is defined as positive angle left and negative right from the

centerline of the image with the thruster at the top of the image. For quantifying the

velocities and taking into account this slight misalignment of the thruster with the image,

four angles are defined. Angle α for the X_Z plane and β for the Y_Z plane are the actual

particle trajectory (red line) angle from the thruster Z axis (dotted line). , The angle the

particle path forms with the image Z axis (black line) is designated angle θ and angle γ is

the angle between the image Z axis and the thruster Z axis as shown in Figure 43.

	Positive angle streak	Negative angle streak
X_Z Plane		

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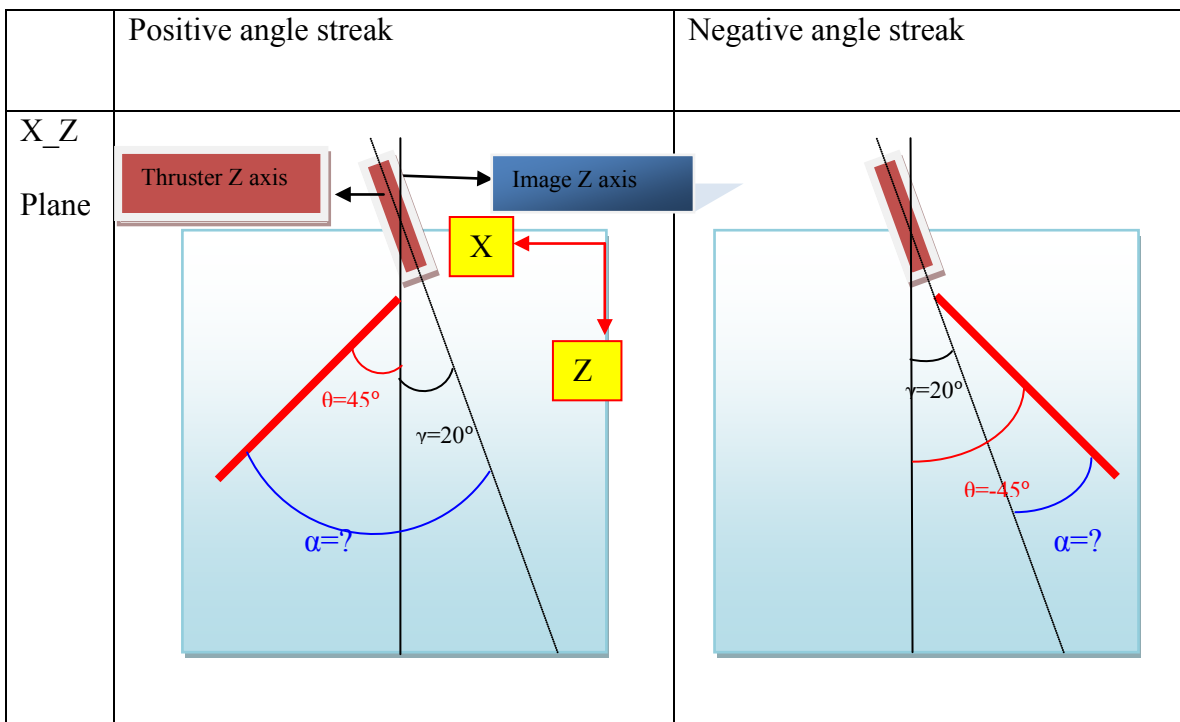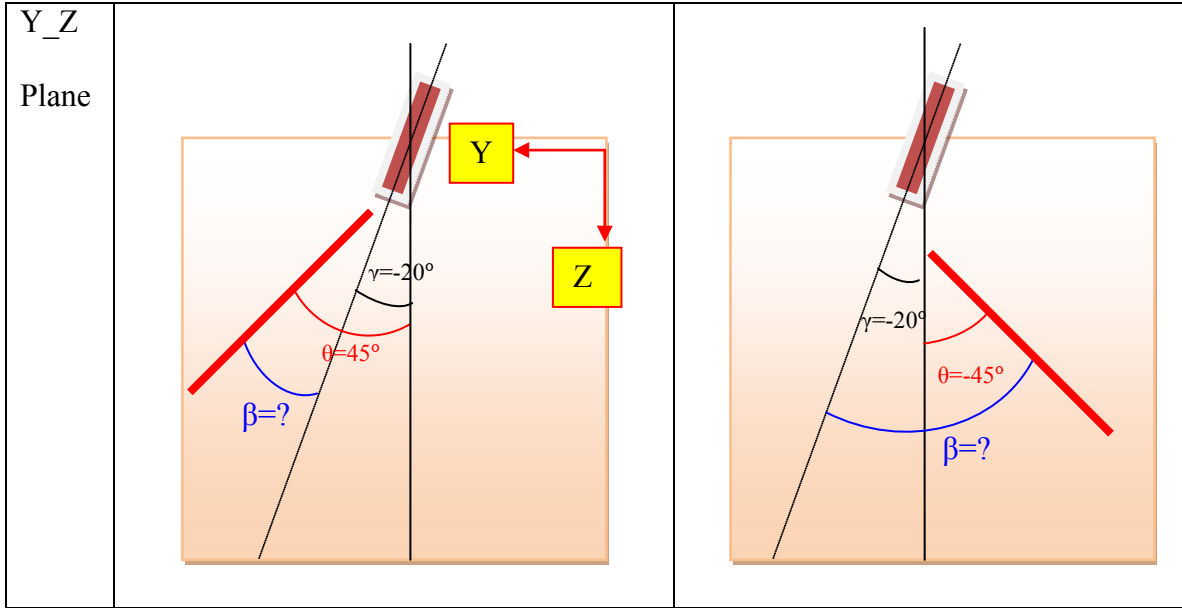
Y_Z Plane	

Figure 43 : Angle Definitions

In case of a positive particle streak angle in X_Z plane (left upper figure), the streak angle (θ) is positive and the image Z axis (γ) is also positive because it is left of the thruster Z axis. We want to know the angle between the particle path and the thruster Z axis (α for X_Z plane and β for Y_Z plane). So the path angle (α) is $\theta + \gamma$ (in the first example, 65º). In the case of a negative particle streak angle in the X_Z plane (right upper figure), the particle has a negative path angle (α) and a positive image Z axis angle (γ) from the thruster. So, the actual particle path angle (α) from the thruster become $\theta + \gamma$ = (-45º) + 20º = -25º. The X_Z plane exhibited only positive γ angles in this research. In contrast, Y_Z plane was captured with negative γ angles. Particle streak angles (θ) were positive and the image Z axis was negative in the left bottom figure corresponding to β of $\theta + \gamma$ = 45º + (- 20º) = 25º. Particle streak angles were negative and image Z axis was also negative in the right bottom figure ($\beta = \theta + \gamma$ = -45º + (-20º) = -65º).

The particle velocities are then resolved from these angles and measured velocities from the images. Designations used for the actual particle velocities are V_x, V_y, V_z, V_{x_z}, V_{y_z}, $V_{x\_y\_z}$. In the image reference frame, intermediate names used were $V_{x\ image\ ref}$, $V_{y\ image\ ref}$, $V_{z\ image\ ref}$, $V_{x\_z\ image\ ref}$, $V_{y\_z\ image\ ref}$ and $V_{x\_y\_z\ image\ ref}$. Velocity with respect to the image are then determined as $V_{x\_z\ image\ ref}$ (red streak) can then be used to calculate V_x and V_z components with respect to the thruster, $V_{x\ thruster\ ref}$ and $V_{z\ thruster\ ref}$ in Figure 44.

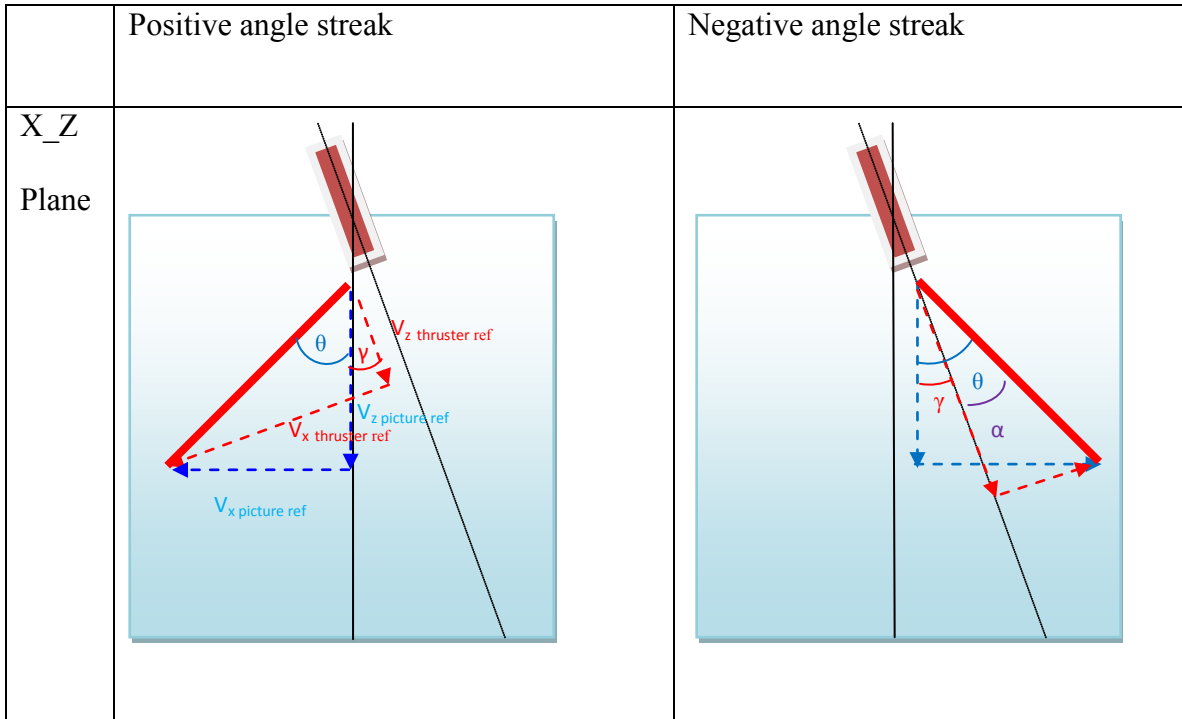|	Positive angle streak	Negative angle streak
X_Z Plane		

Figure 44 : Velocity Component in Thruster Coordinates.

We know the angle α equals θ + γ. So the $V_{x\ thruster\ ref}$ and $V_{z\ thruster\ ref}$ are determined as below.

$$V_{x,thruster\ ref} = V_{x\_z,picture\ ref} \sin\alpha \qquad (2)$$

$$V_{z,thruster\ ref} = V_{x\_z,picture\ ref} \cos\alpha \qquad (3)$$

It can also apply to Y_Z plane.

$$V_{y,thruster\ ref} = V_{y\_z,picture\ ref}\sin\beta \qquad\qquad (4)$$

$$V_{z,thruster\ ref} = V_{y\_z,picture\ ref}\cos\beta \qquad\qquad (5)$$

IV.5. **Velocity Distribution**

The radial and axial velocity components as well as magnitude of all particles is calculated using physical particle path length and exposure time as mentioned in chapter 3. The data is sampled using an average velocity with proper ranges for each velocity component and approximated with a normalized distribution using a Gaussian function. Added to the error quantified from the data analysis technique and system bias, variations are quantified from the statistical distribution of the results. Normalized distributions for each data set were fit to the data by varying the mean (*b*), scale (*a*) and standard deviation (*c*) of Gaussian function:

$$f(x) = ae^{\frac{-(x-b)^2}{2c^2}} \qquad\qquad (7)$$

The scale (*a)* represents the height of the curve's peak while mean (*b)* is the position of the center, and (*c)* changes the width of the bell shaped graph[21].

IV.5.1. Comparing 3D Velocity Distributions with Previous 2D Velocity Distributions

The velocity distribution at 4V input voltage (2J) is shown in Figure 45. The distribution of the velocity for the radial components is similar to the distribution for the velocity magnitude and axial distribution but with smaller standard deviations for the Gaussian distributions as shown in Figure 45. These results agree with previous result for the 2D velocity distributions. The velocity distributions exhibit two distinct regions. One region, for velocity magnitude distribution (below 300 m/s) appears to follow a trend

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with a 110 m/s standard deviation. Higher speed particles (above 300 m/s) have a

standard deviation of 130 m/s. Previous results only exhibited one normal distribution.

The same trend was present at all operating conditions. The other Figures for each energy

level will be presented in Appendix B.

Radial Velocity Distribution	

Axial Velocity Distribution	
Velocity Magnitude Distribution	
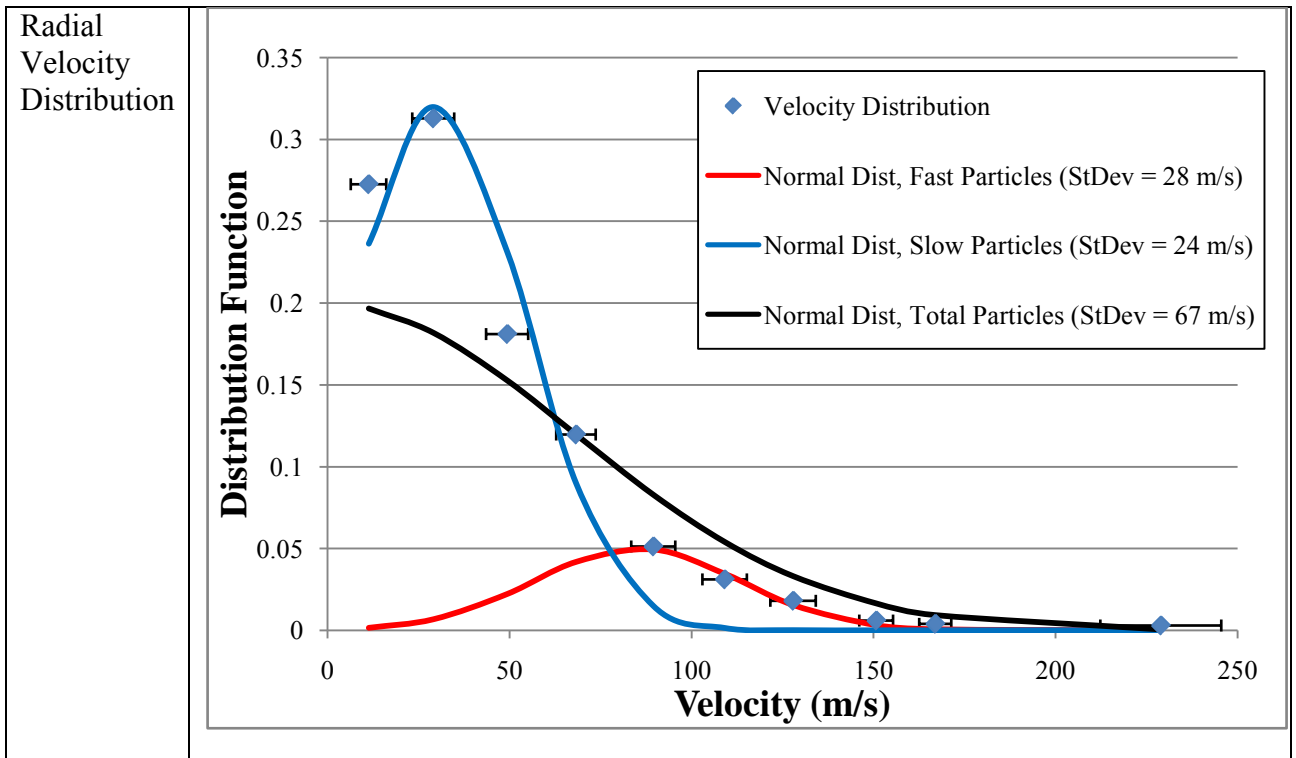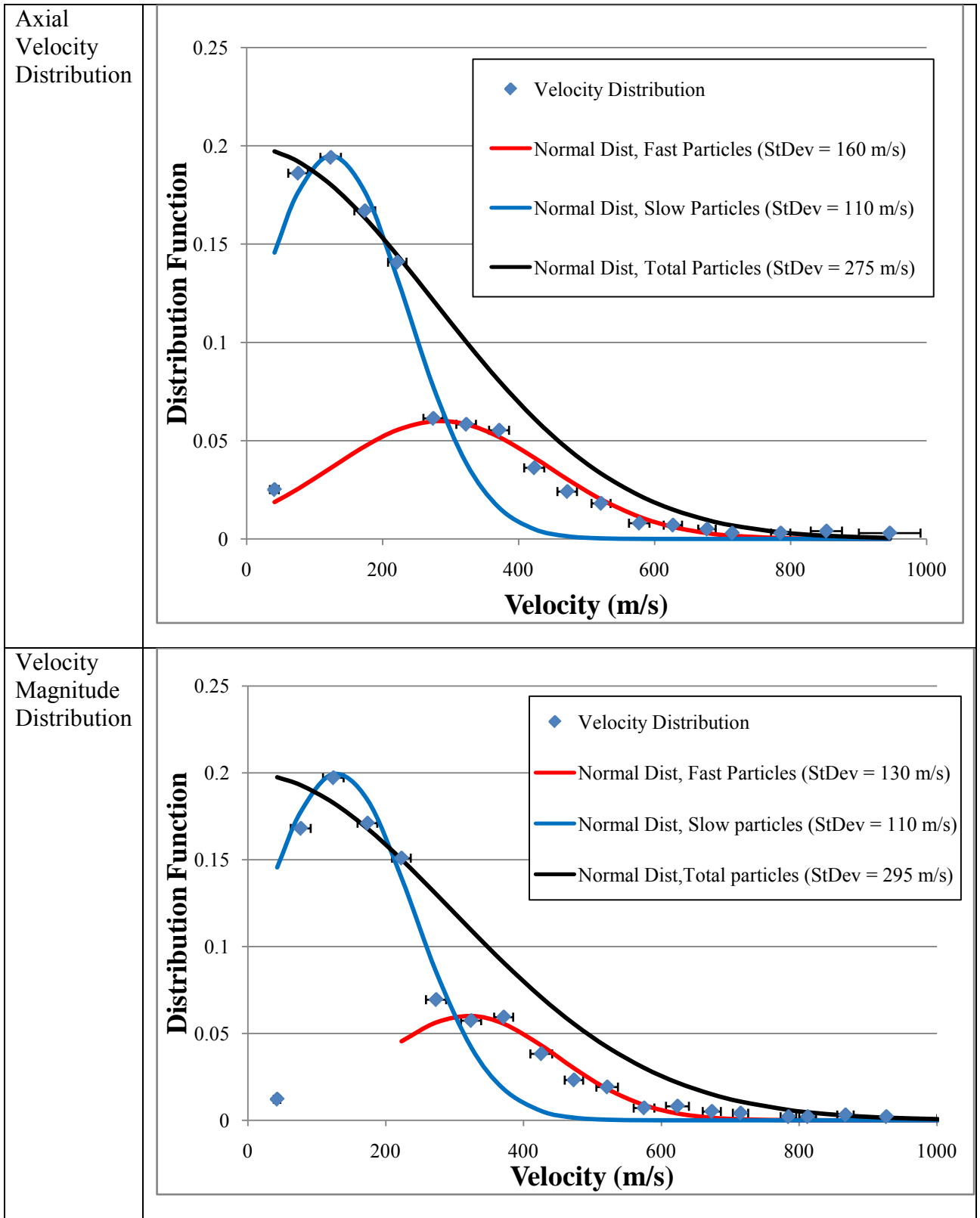
Figure 45 : Velocity Distribution at 4V (2.2J)

IV.5.2. Compare Velocity Distribution with Each Energy Level

The velocity distributions will be compared with each energy level for each velocity component. As shown in Figure 46, it looks similar to other velocity data which means the energy does not directly affect the velocity distribution of the emitted particles. The particles are being ejected by the expansion of the gas at the surface but the high speed ionized gas is not adding any further momentum to these particles.

Radial Velocity Distribution	

Axial Velocity Distribution	
Velocity Magnitude Distribution	
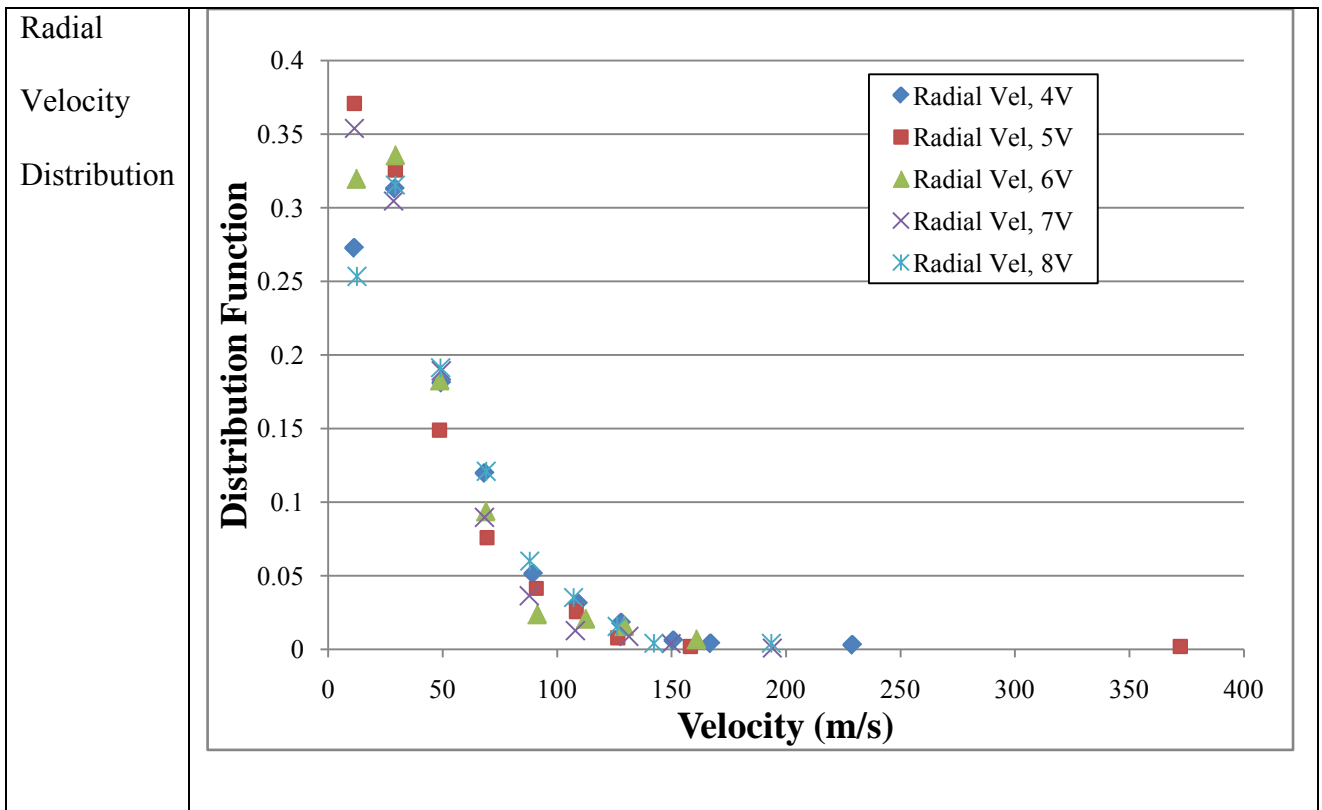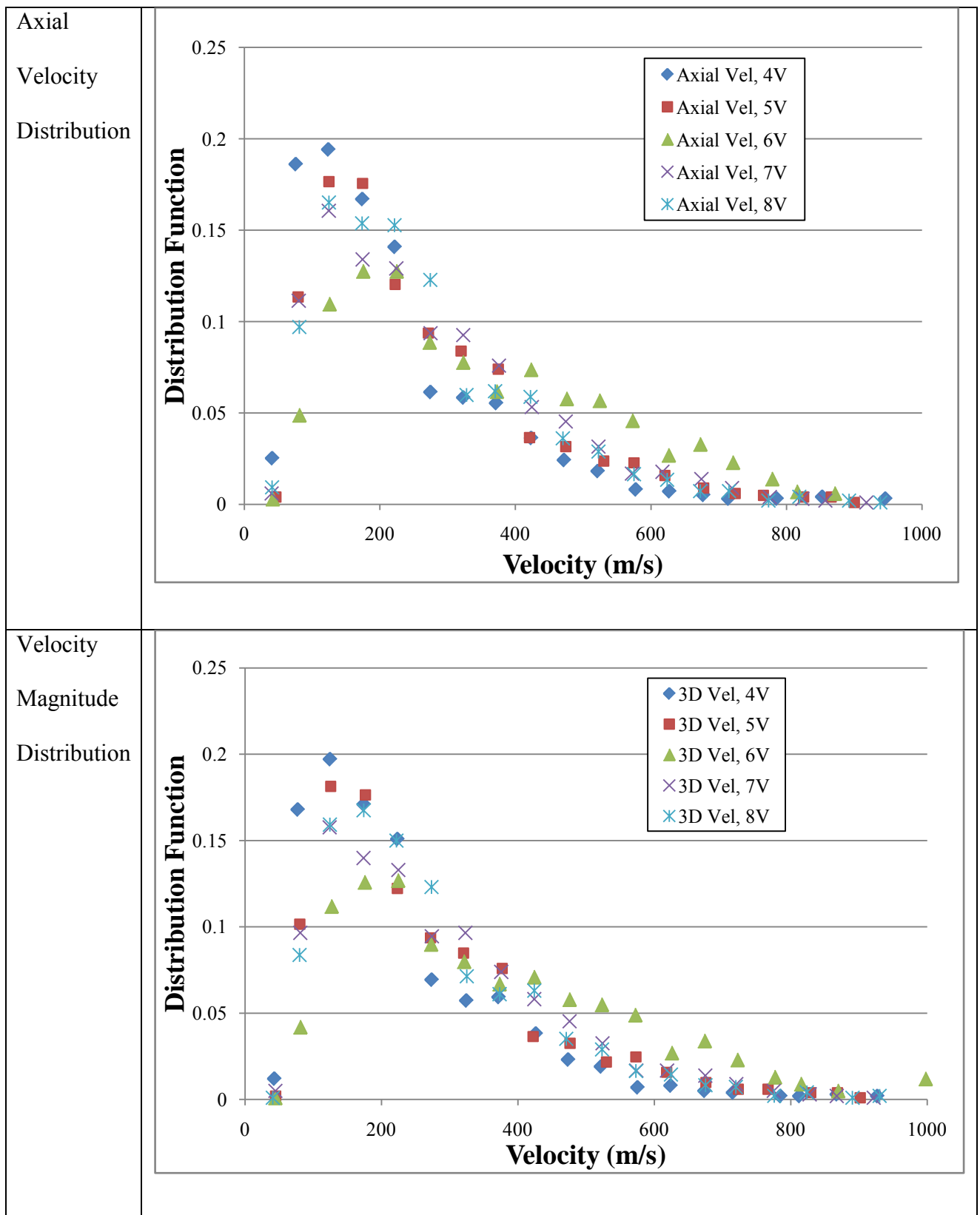
Figure 46 : Comparing Velocity Distribution With Each Energy Level.

IV.5.3. Performance Contributions

One can calculate specific impulse (I_{sp}) values with known gas exit velocity. When assuming the particles which have an axial direction velocity component contribute the total thrust, I_{sp} contributions can be estimated from the average axial velocity using the following equation:

$$I_{sp} = \frac{v_{ex}}{g_0} \qquad (8)$$

Table 12 shows the average velocity and I_{sp} contribution for each energy level. As shown in the table, the maximum I_{sp}, 35 sec, occurs at 3.4J. Even though this might suggest an optimal operation for this thruster, the variation in the measurements and the statistical variance in the results suggest only the solid particulates being ejected provide an additional 25 – 35 seconds of I_{sp}.

Table 12 : I_{sp} Contributions for Each Operating Conditions

Input voltage (Energy)	4 V (2 J)	5 V (2.7 J)	6 V (3.4 J)	7 V (4.0 J)	8 V (4.4 J)
Average axial velocity (m/s)	215	256	345	270	258
Isp (sec)	22	26	35	28	26

IV.6.   Angle Distribution

The solid angles of the particles were also analyzed using the same velocity data. Solid angles can simply be determined from the velocity components. We know all velocity components such as radial and axial components with respect to the thruster from the velocity data. Solid angle is determined directly from the trigonometric function:

$$\Omega = \tan^{-1}(V\ x\_y\ thruster\_ref\ /\ V\ z\ thruster\_ref) \qquad (9)$$

The solid angle (Ω) is 36 º using the example equation $\tan^{-1}((2^2+3^2)^{1/2}\ /\ 5)$ in Figure 47.
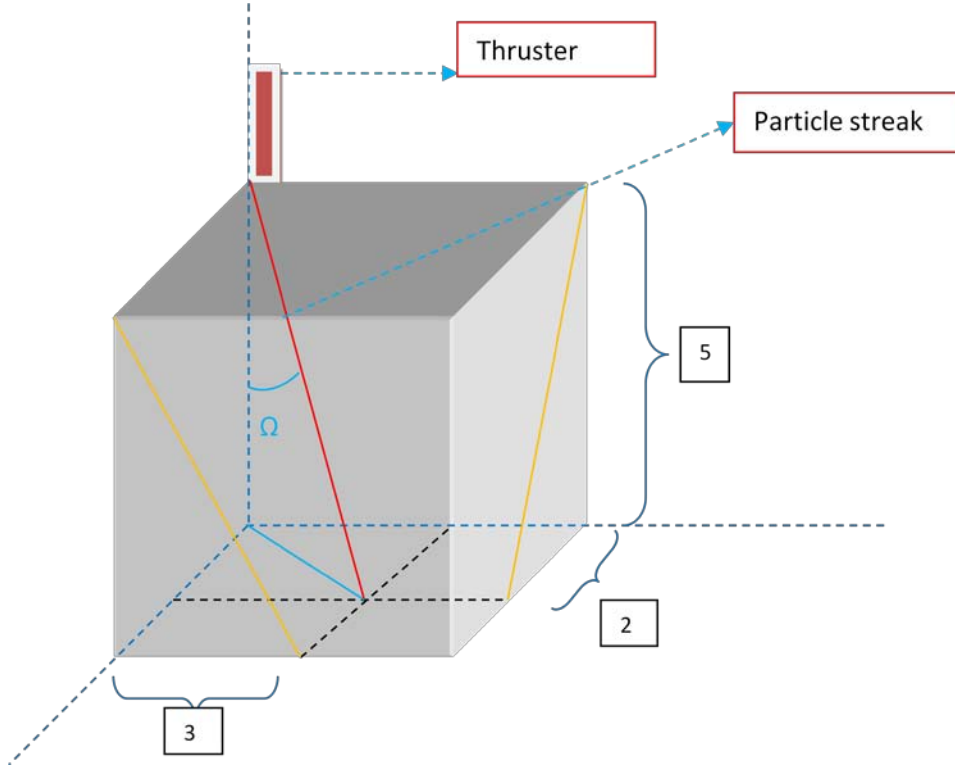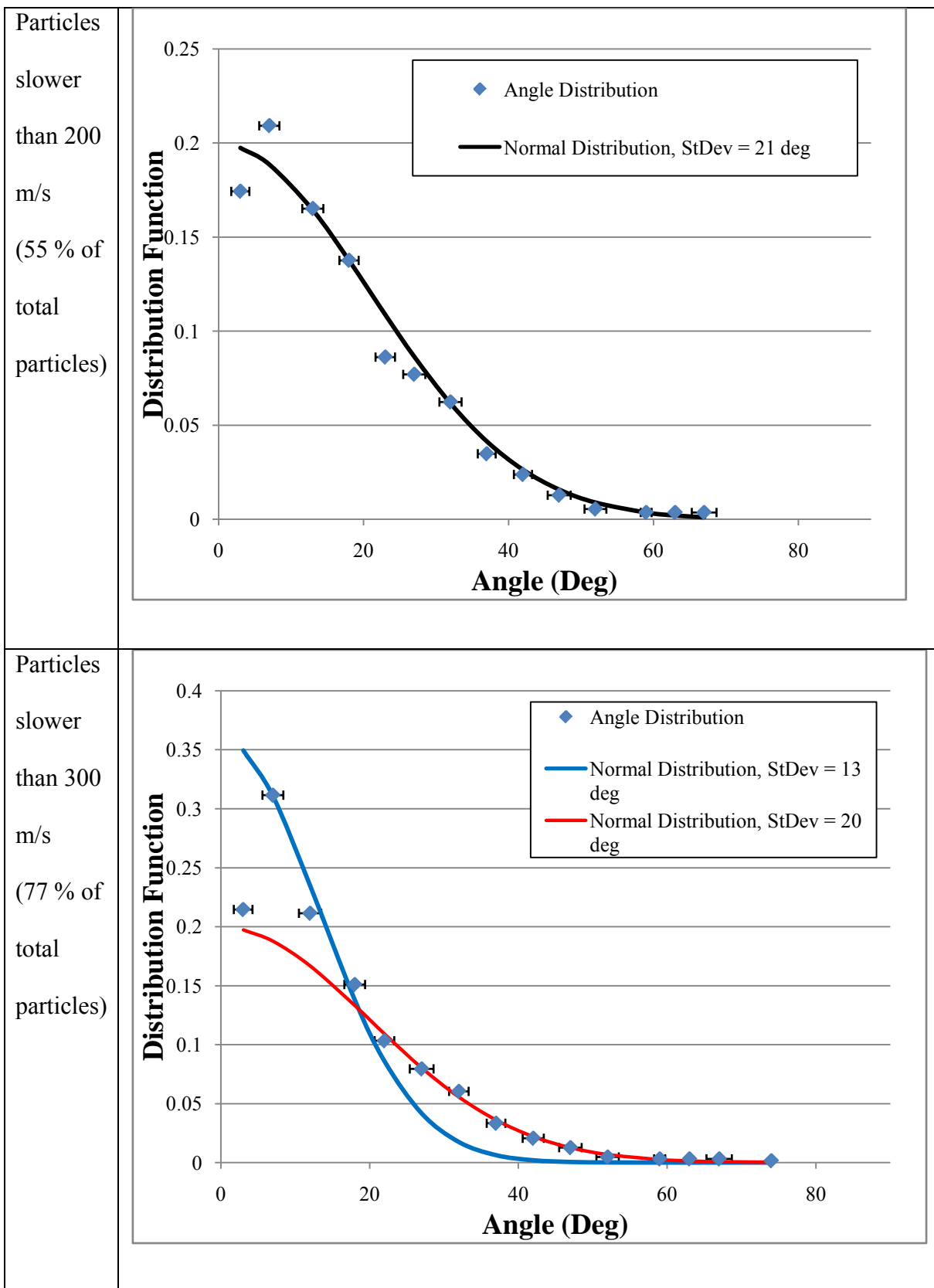

Figure 47 : Solid angle calculation

The angles were sampled similarly to the velocity data to create distribution functions using average values of proper ranges, 5 degrees per range in this study. Normal distributions for the angle data were made using the same technique as for velocity distribution. The graph was also adjusted using parameter *a, b* and *c* to fit the sampling data.

IV.6.1. Comparing Solid Angle (3D) with 2D Angle Distribution

The solid angle distributions are shown for the particles slower than 200 m/s, slower than 300 m/s and faster than 300 m/s at 4V input voltage in Figure 48. Other angle distributions for other energy level will be shown in Appendix C.

The result matches previous results based on mass deposition tests with a two-electrode micro-PPT as shown in Figure 14, Figure 15 and Figure 16 in chapter 2. However, this research is different from these results in that the angle distribution peaks around 45 degrees for slow particles as shown in Figure 9. The particle count peaks at around 10 degrees when all particles are considered in this research. A significant difference between previous and present research is the data was obtained for different micro-PPT designs. Previous research used a two dimensional result for the two-electrode micro-PPT. However, the data here is obtained from three-dimensional space and three-electrode micro-PPT in this research. There is also a difference of energy operating conditions used for each test but the energy is not affecting the angle distribution which will be explained next.

Particles slower than 200 m/s (55 % of total particles)	
Particles slower than 300 m/s (77 % of total particles)	

Particles faster than 300 m/s (23% of total particles)	
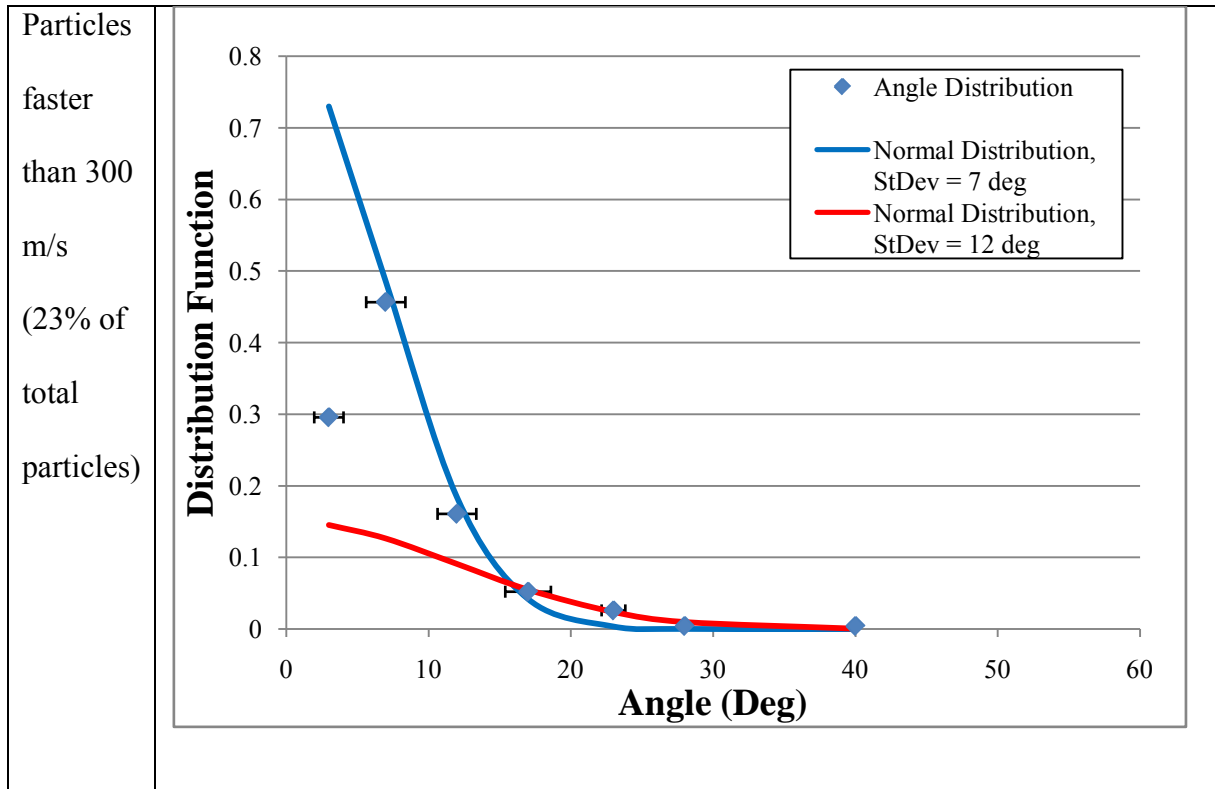
Figure 48 : Angle distribution at 4V (2J)

The normal distribution fit to the results suggests the particle counts peak at 0 degree but the data show a reduction of the number of particles below 10 degrees. The design of the thruster is the primary reason for this relationship. The three-electrode micro-PPT has three electrodes. The center and intermediate electrodes provide the intermediate discharge. This discharge will generate gas at this surface along the centerline which will start to expand before particles and gas from the main discharge are generated. This expanding gas will naturally push the particles away from the thruster centerline. Michael Keidar and Iain D. Boyd developed a model for the plasma plume in near field of this type of thruster. They used the two electrode micro PPT for their working example. The electromagnetic (jxB) acceleration is the main mechanism in this thruster. Therefore, the near-field plasma plume is a crucial part of the thrust generation

process[22]. These researchers showed results of Carbon and Fluorine (components of this propellant) ion density decreasing with radial distance as shown in Figure 49.

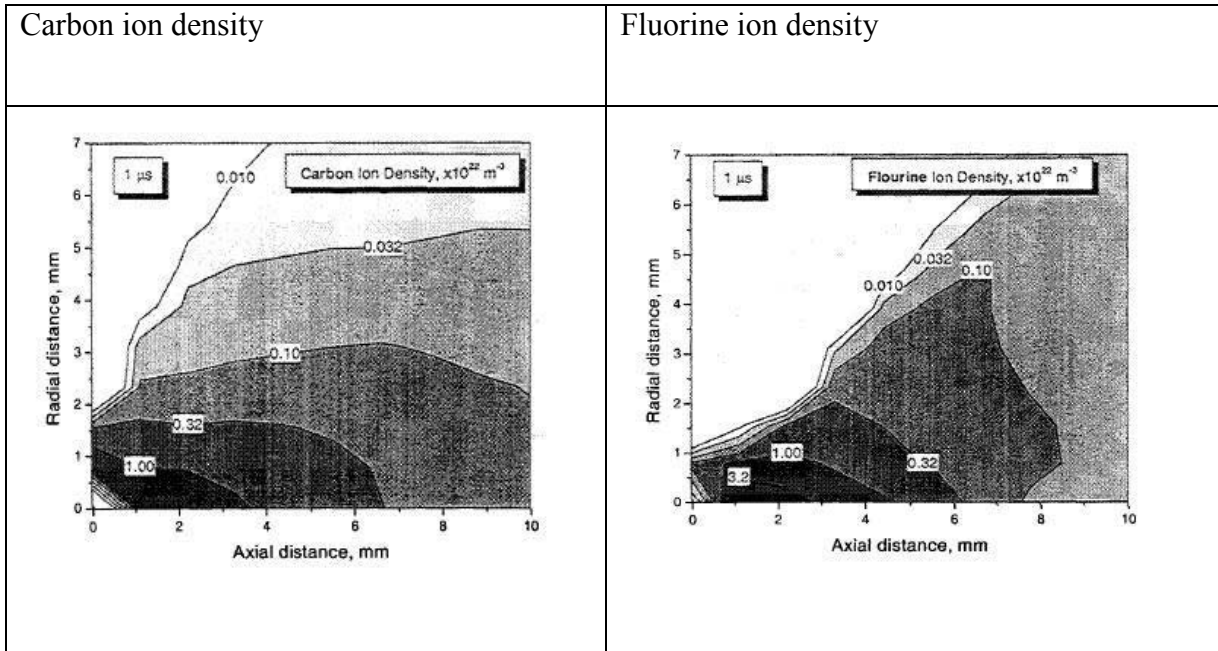| Carbon ion density	Fluorine ion density

Figure 49 : Profile of ion density at 1 µsec after firing[22]

From the result of the plume profile of the two-electrode micro-PPT, one can expect the plume of the three-electrode micro-PPT as shown in Figure 50 to behave similarly. Particles from main discharge will be deflected in a similar fashion as the plume of the thruster expands, Figure 50.

The diagram shows a three-electrode micro PPT structure labeled with "Teflon" sections, "Center electrode", "Intermediate electrode", and "Outer electrode". The red plume region shows C^+ F^+ ions. A callout box reads: "Carbon and Fluorine ion from intermediate discharge between the central and intermediate electrode".
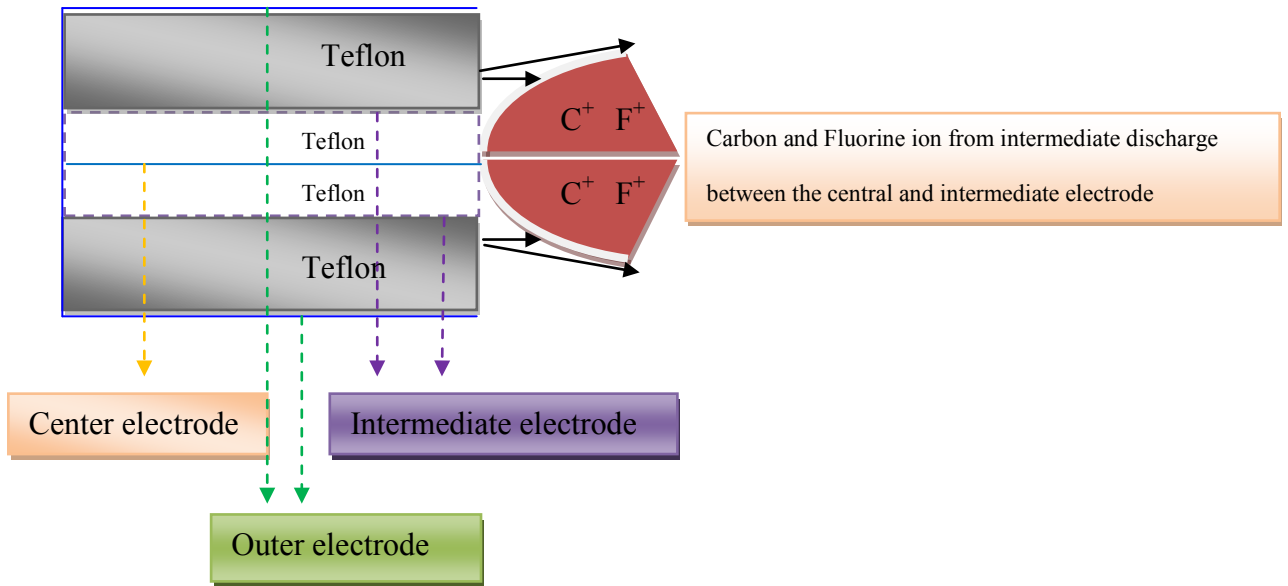
Figure 50 : Profile of plume from the main discharge of three-electrode micro PPT

IV.6.2. Comparing Solid Angle Distribution With Different Energy Levels

The angle distributions are compared at different energy levels in Figure 51. These profiles also have similar profiles to each other suggesting energy does not affect the angle distributions appreciably at these operating conditions, the same conclusion as that of velocity distributions.

Particles angle distribution slower than 200 m/s	
Particles angle distribution slower than 300 m/s	

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| Particles angle distribution faster than 300 m/s | |
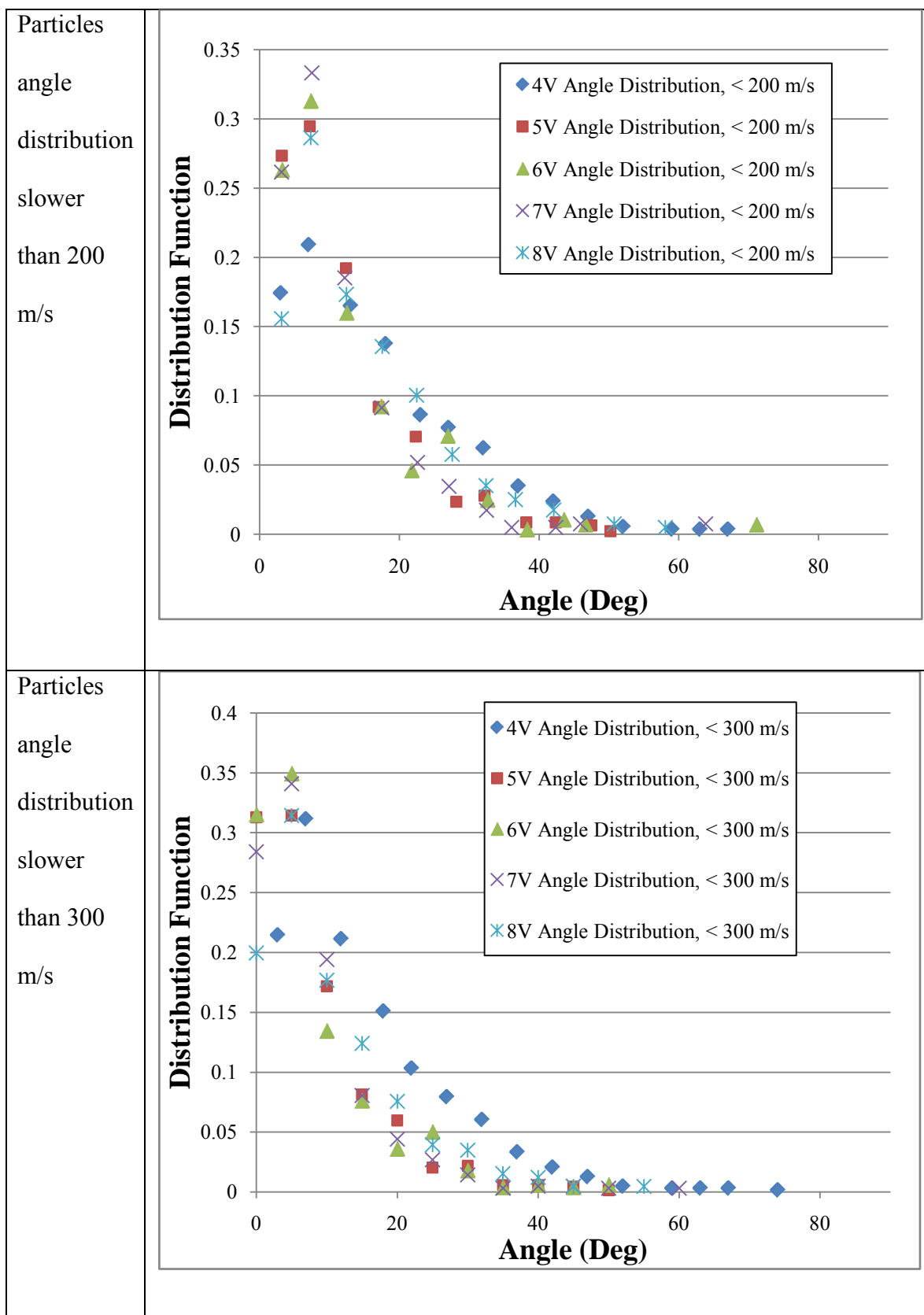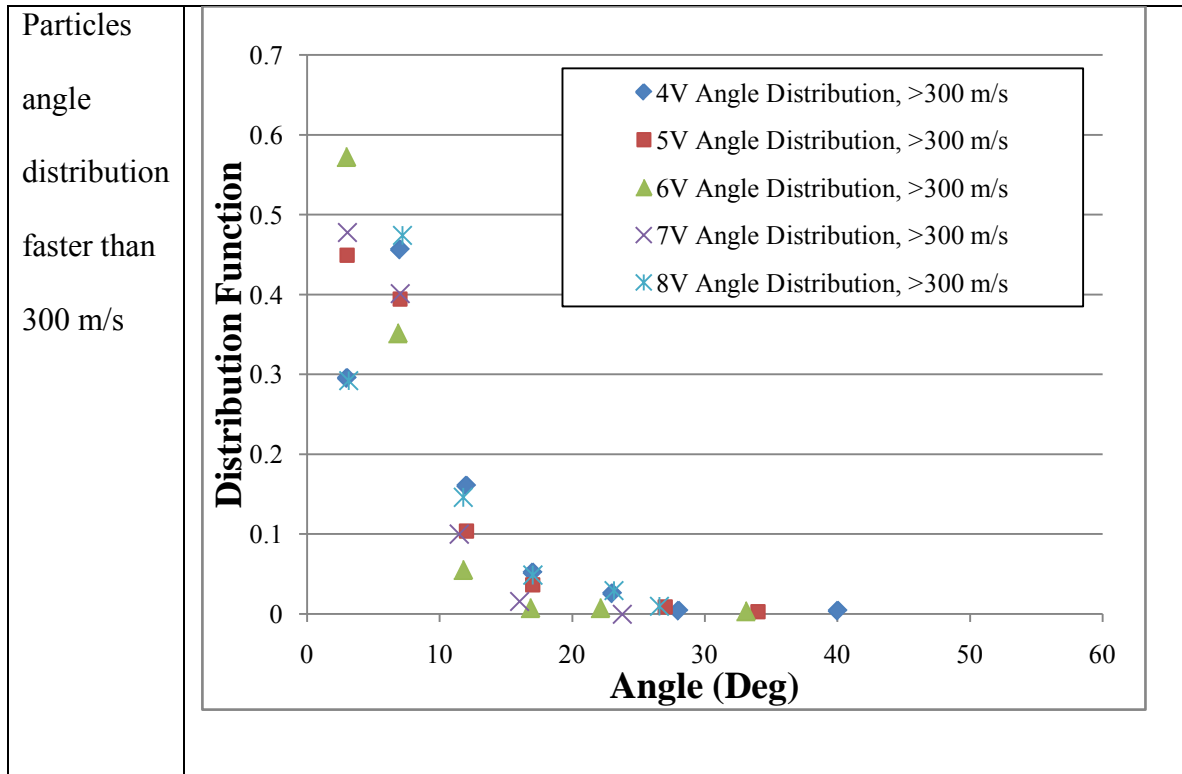
Figure 51 : Comparing angle distribution with each energy level.

IV.6.3. Average Velocity Versus Angle Range

To explore the relationship between particle velocity and angle distribution, average velocity versus angle range for each operating condition was calculated and shown in Figure 52. The data shows the shallow angles have higher average velocities. One can also see the average velocity profiles of each energy level are similar to each other

Average velocity Vs Each angle range
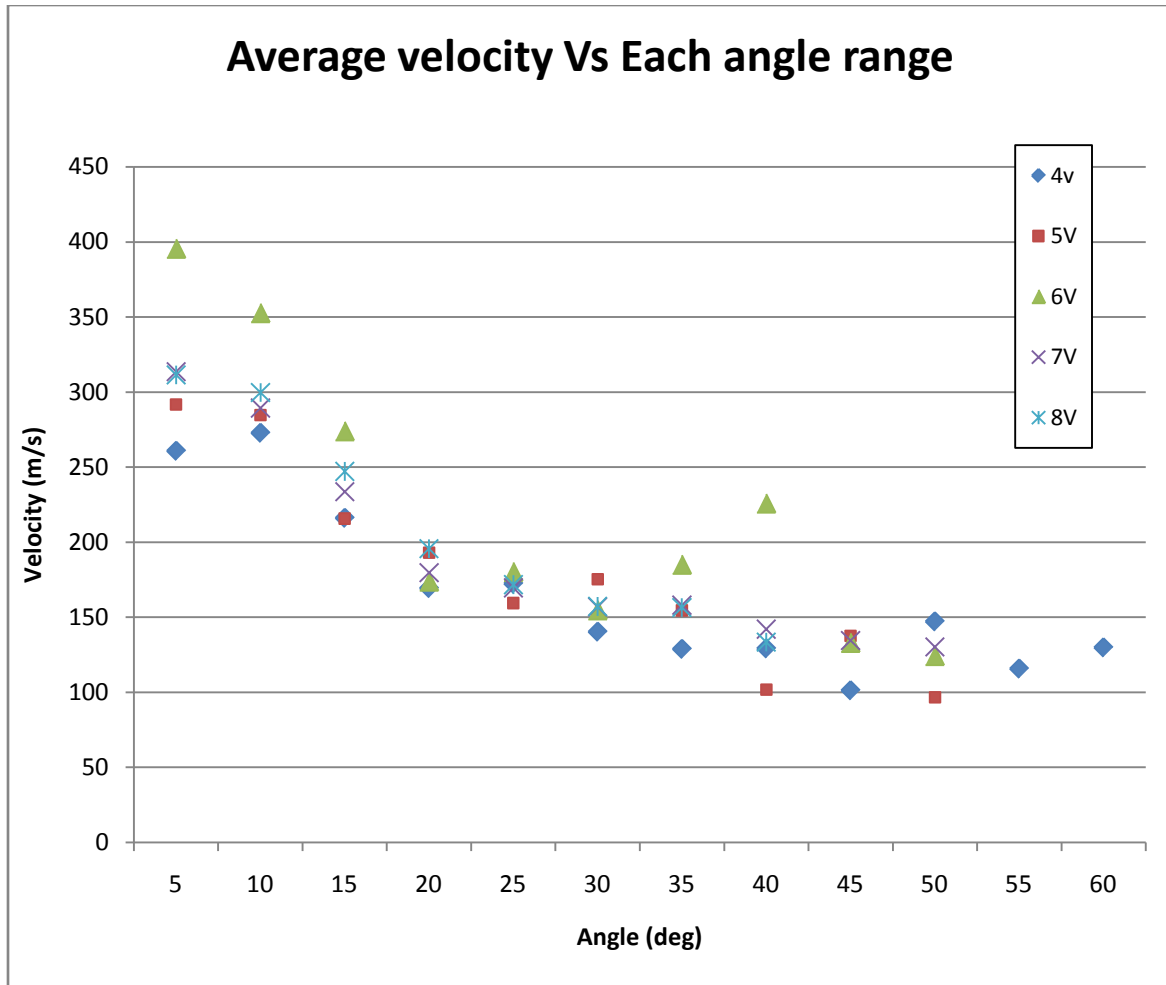
Figure 52 : Average Velocity Versus Angle

The velocity standard deviation of these particles for each angle range was also examined. Figure 53 shows the particle's standard deviation of velocity as function of angle. The standard deviation shows particles exiting closer to the centerline (shallower angles) have larger values for standard deviation as we expected suggesting the velocity for these particles are varies over a wider range. One can also see standard deviation of velocity does not depend on discharge of energy for the thruster. The fastest particles exit closer to the center line as can be seen from the results and the standard deviation of the velocity distribution. The larger standard deviation for the particles exiting near the

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centerline suggest both slow and fast particles are exiting near the centerline, at shallower angels. The relatively lower velocity variance at more divergent angles (steeper angles from the centerline) suggests only slower particles are present.
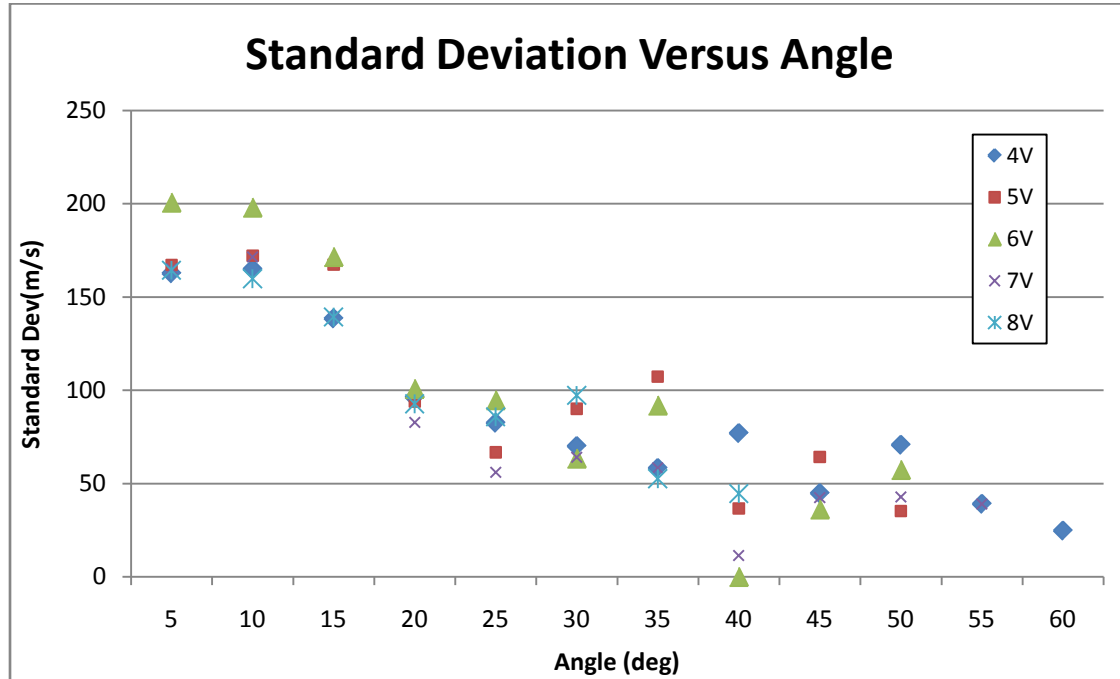
Figure 53 : Standard Deviation Versus Angle

IV.7.   **Summary**

Both intermediate and main discharge energy levels are important to operate the reliable three-electrode micro-PPT. This research used only one intermediate discharge energy level, 0.002 Joule and varied the main discharge energy level from 0.1 to 4.5 Joule. The main discharge energy ranged from 2 to 4.5 Joule and provided good results for firing the PPT. Velocity and angle distributions were analyzed for each energy level using the particle data from the high-speed cameras. The data shows the angle and velocity distributions were not appreciably affected by energy levels explored by this

research. However, the particles do contribute to I_{sp}. Particle counts for the angle range from 0 to 10 degrees is not the highest distribution in a three-electrode micro-PPT, a different result from previous mass deposition profile results using a two-electrode micro-PPT.

V. Conclusions and Recommendations

V.1.   **Overview**

Conclusion for the three-electrode micro-PPT operability, velocity and angle distribution and energy effects on this distribution will be summarized. The performance contribution from particle velocity and relationship between velocity and angle will be concluded. To get a more reliable data and for future work, some recommendation are also provided.

V.2.   **Conclusions**

V.2.1. Operability

The three-electrode design was tested to determine if it is more reliable than a two-electrode micro-PPT or not. When using the three-electrode micro-PPT, it proved more reliable than a two-electrode design. Three-electrode micro-PPTs worked whenever the seed ionization (using 0.02 Joule intermediate discharge energy) was triggered and the main discharge energy was sufficient (4 V input, 2 Joule). A two-electrode micro-PPT was operated intermittently for this research as high as an energy level of 4.5 Joule. The energy range for a reliable thruster operation was from 2 Joule to 4.5 Joule in this research.

V.2.2. Velocity and Angle Distribution

Velocity distribution helps understanding the contribution to thrust provided that the mass consuming rate is known. It also provides the particle behavior and potential

vehicle contamination. The faster particles have shallower angles than slower particles and the standard deviation of shallower particles is higher than the steeper particles.

This research showed similar results for angle distributions to previous mass deposition distributions. From the point of view of a contamination issue, it supports the previous conclusion that sensitive equipment such as solar array, optical instrument and star tracking cameras should not be placed within 60 degrees of this type of thruster.13

V.2.3. Performance contribution

The solid particulates being ejected from the three-electrode micro-PPT provide an additional 25 – 35 sec of I_{sp} when varying the energy levels.

V.2.4. Energy Effect on Angle and Velocity Distribution

The velocity and angle distributions did not show significant effects from a varying energy operating condition.

V.3. Recommendations

V.3.1. Operability and Circuit Design

Further studies are needed to optimize seed energy to determine the minimal energy consumption for this device. Typically, the trigger discharge energy is about 2% of the main discharge energy level8. The seed energy was set at 0.002 Joule (8 kV output voltage and 50 pF capacitor) for this research, far below the 2% (0.1 – 0.2 % of the main discharge energy in this research). The seed energy can be varied by adding an external capacitor to the same HV pulse generator input.

V.3.2. Capturing the Particles

A better camera able to capture a larger plume area can improve the results and increase the number of particles captured with the same interrogation area. Limited area for the image decreases the data accuracy for both velocity and angle distributions. It was difficult to capture the same particles from the both camera. Being able to synchronize both cameras easily will also reduce errors introduced from frame rates and exposure times which means the particles have same positions (coordinates) and same length in Z direction at the same frame.

V.3.3. Velocity Distributions and Performance Contribution

Particle Image Velocimetry (PIV) could also be used to automate the process of converting observed particles to velocities. Automatic software saves a lot of time converting the row data to particle velocity if available. This well developed ability can capture more particles and provide more reliable data.

Tests to quantify mass consumption rate will also provide a missing piece of the performance equation;

$$F = (\dot{m} \times Vexit) \tag{10}$$

Where, F is thrust, $\dot{m}$ is propellant consumption rate and $Vexit$ is propellant exit velocity.

The contribution to I_{sp} in this research is small when comparing to total PPT I_{sp} values for thrusters such as the LES 8/9's 1000 sec or NOVA's 850 sec[23]. Actual thruster I_{sp} values can be adjusted, though, by the contributions measured here. A measured thrust value from a torsional balance will give more quantifiable ways to determine propellant exit

velocity of the micro-PPT and the contribution from the average value of particle's velocity after measuring the propellant consumption rate.

V.3.4. Angle Distributions

More tests using three-electrode micro-PPT focusing on mass deposition rate as well will provide valuable information contamination issue. This research focused on providing accurate data for axial image along with the thruster. For contamination standpoint, focus on radial image of the particles becomes very important. For that, it needs the particles capturing using the camera set of right upper side in Figure 32.

Appendix A: **Camera Operation**

To operate the cameras, make sure all cable connections are good and open the Motion Pro software. Select the "Cameras" in Figure 54 and click the "open" in Figure 55. All connected cameras will appear in the box.
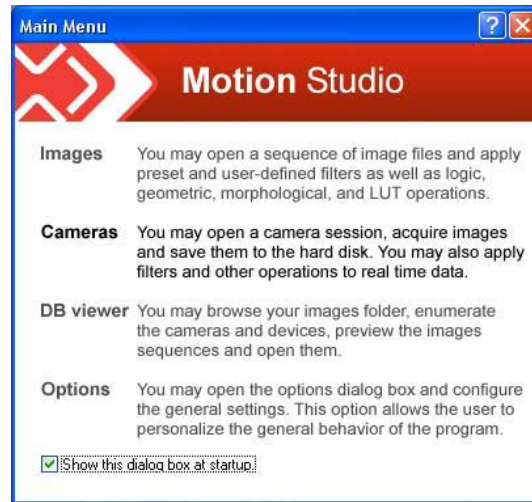

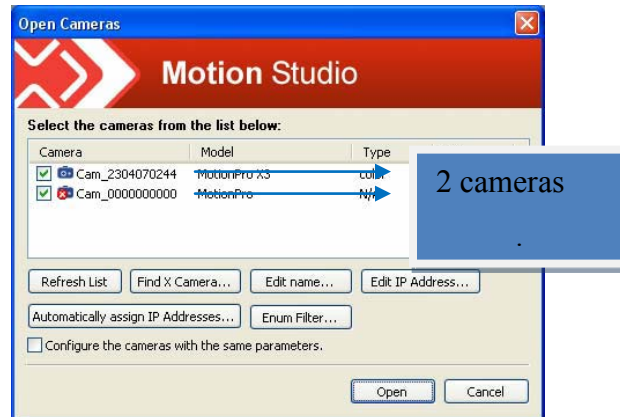Figure 54: First screen of Motion Pro software when it opens

Figure 55: After selecting the "Cameras"

There are four main menus as shown in Figure 56; live, playback, camera and record. The live menu provides functions such as record, live, stop and trigger. The "Trig" button can only be activated after hitting the "Rec" button when the record mode is selected as "circular" or "BROC". The "Live" button in live mode is for real time play

of the object, which is used for previewing the thruster with low light mode before taking pictures to set up the experiment. The "Rec" button in live menu can be used for activating the trigger when everything is ready for taking picture. The only thing left for taking pictures is hitting the "trig" key on the function generator, then the "trig" button in live menu will be executed.

The playback menu may be used for reviewing the image saved in the camera. To get the desiring images, camera and record menus should be set properly. There are several options in the camera menu such as sensor gain, reset, rate, exposure, gamma, exposure mode and ROI as shown in Figure 56. Sensor gain is for selecting a gain value ranging from "-6 dB" to "+3 dB". For this research "no gain" is employed throughout. The pulse event generates sufficient light for particle capture. If a device IO control error message appears, clicking the reset button may be helpful. The reset button restores the camera from the error condition. To select a new frame rate value, use the rate drop-down list. If the current exposure is too large for the selected rate, the program automatically adjusts it to an acceptable value. In this tab, the exposure time and f-stop values can be set. The ROI button is important to note again because of the relationship between the maximum frame rate of the camera and the number of rows in the ROI. In record menu, there are three record modes; normal, circular and Burst Record on Command (BROC). Normal mode records when the "Rec" button in live menu is set. The camera waits for "trig" button in live menu to complete the acquisition of the image in Circular and BROC modes. The difference between Circular and BROC is that memory is divided into sub-segments in BROC mode. The camera acquires images in a circular mode in sub-

segments. When the "trig" button is set, the camera completes the acquisition of images and starts acquiring in a specified sub-segment until the memory is filled. BROC mode is very useful if the trigger is supplied to the camera and thruster repeatedly. Initial attempts using BROC mode with the trigger set to 1.0 Hz did not provide the desired results. When triggering the two cameras using BROC, one camera took one picture but the second camera took two images, providing a difference in the actual time of the different images. The cause was not identified but the speculation is that one camera is more sensitive than the other when receiving the signal from function generator trigger. The research employed the circular mode effectively, but did require researcher interaction, clicking the "Rec" button in live menu, "trig" button in function generator and saving it on the computer for every single shot. .

The frame option in the record menu is the number of frames to be recorded to the camera memory in a single acquisition. The values can be set from one up to a maximum number depending on the amount of free memory since single event captures occurred over millisecond time frame, most tests only capture 20 frames per event. In BROC mode, the number of frames is then further divided into each sub-segment. For instance, if the number of frames is set to 1000 and the BROC length is set to 100, the camera will acquire 10 sub-segments.
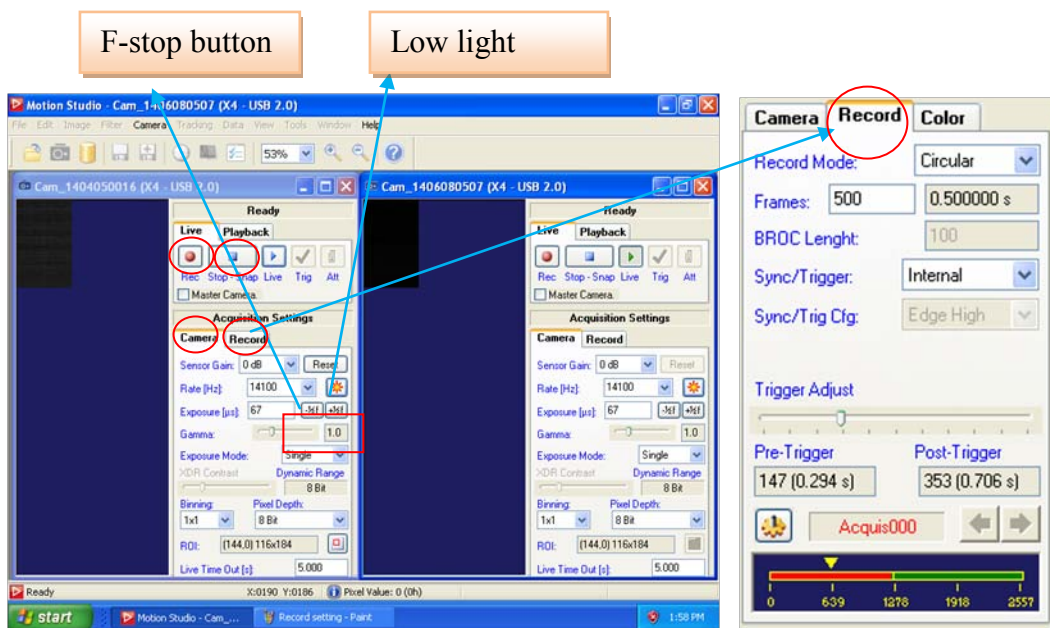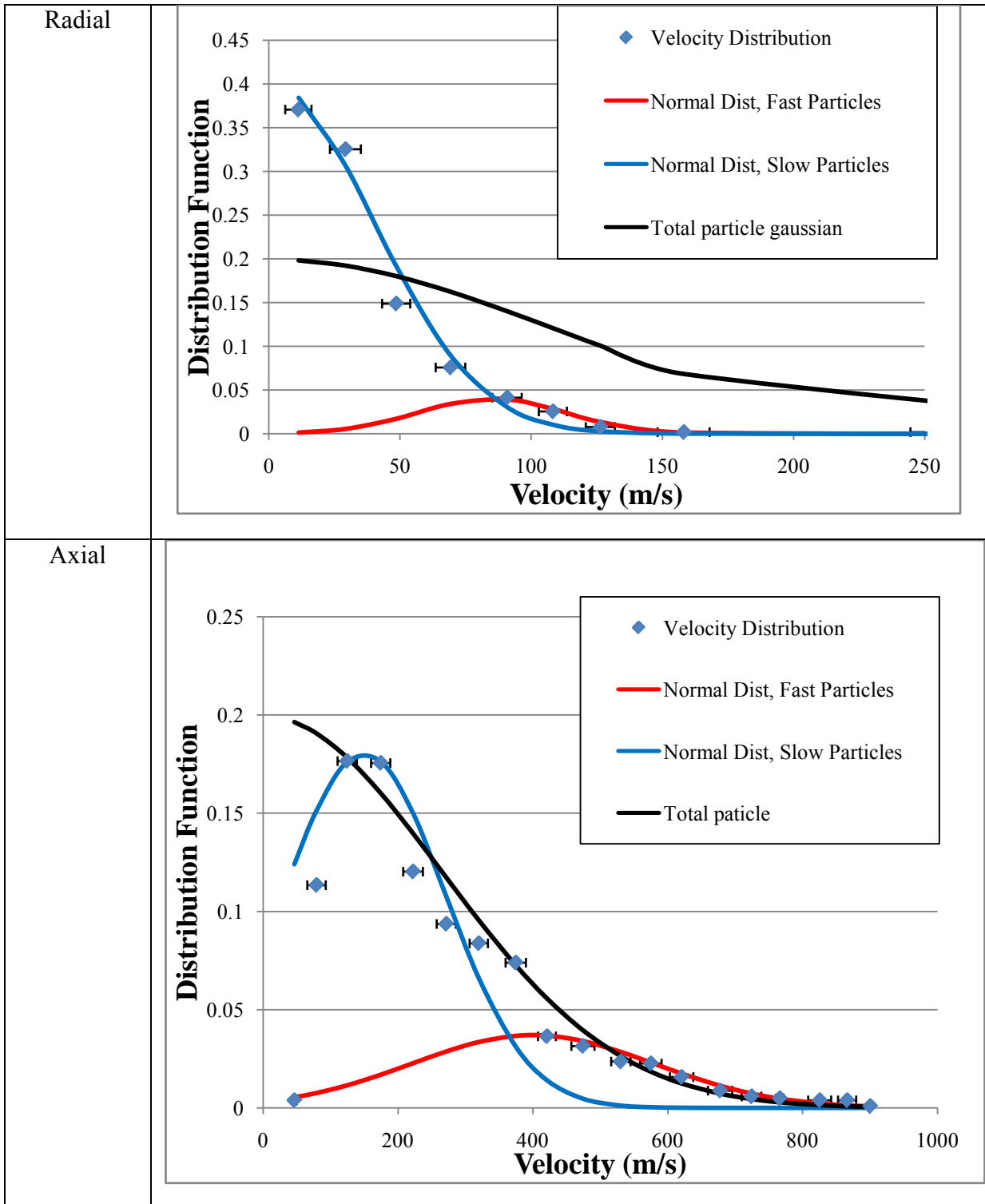
Figure 56: Screen after clicking the "open"

Appendix B: Velocity Distribution for Each Energy Level
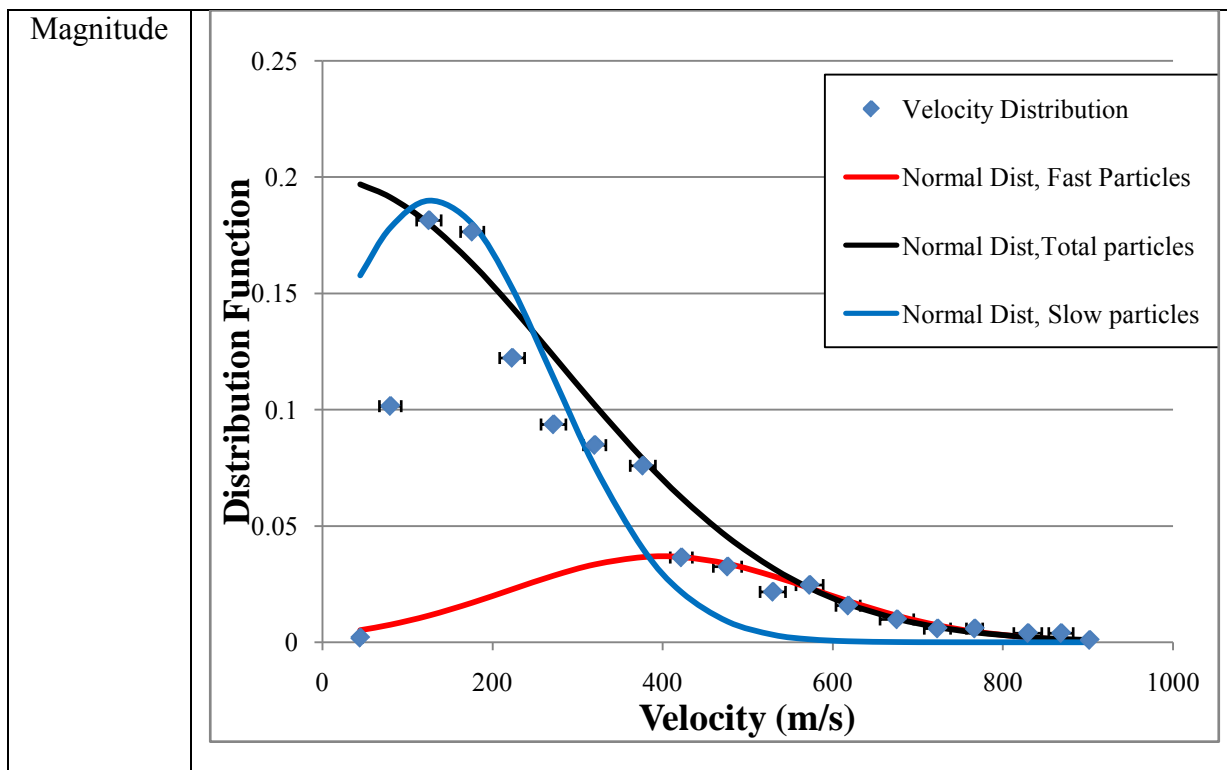
5V (2.7 Joule)

| Magnitude | |

Figure 57 : Velocity Distribution for 5V (2.7 Joule)
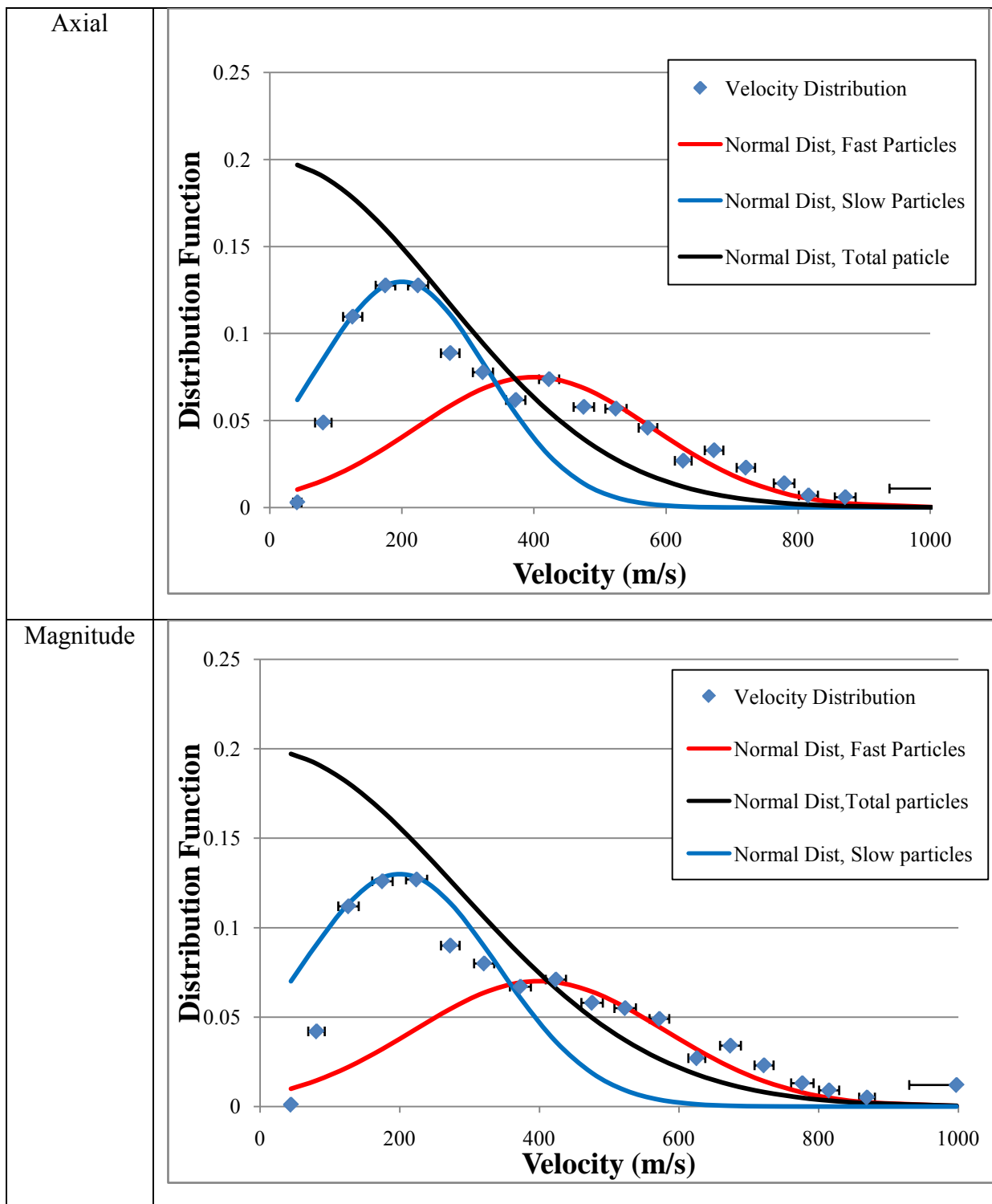
6V (3.4 Joule)

| Radial | |

Axial	
Magnitude	
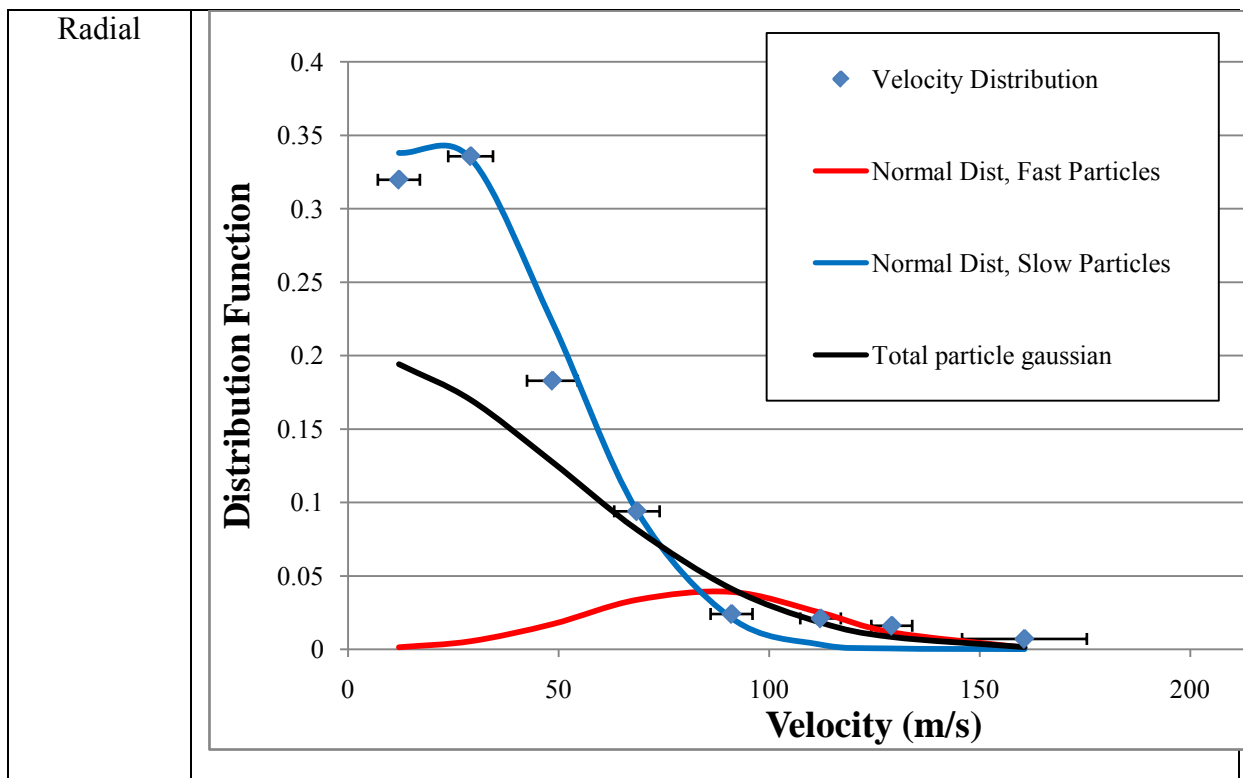
Figure 58 : Velocity Distribution for 6V (3.4 Joule)

7V (4 Joule)

Radial	
Axial	

Magnitude	
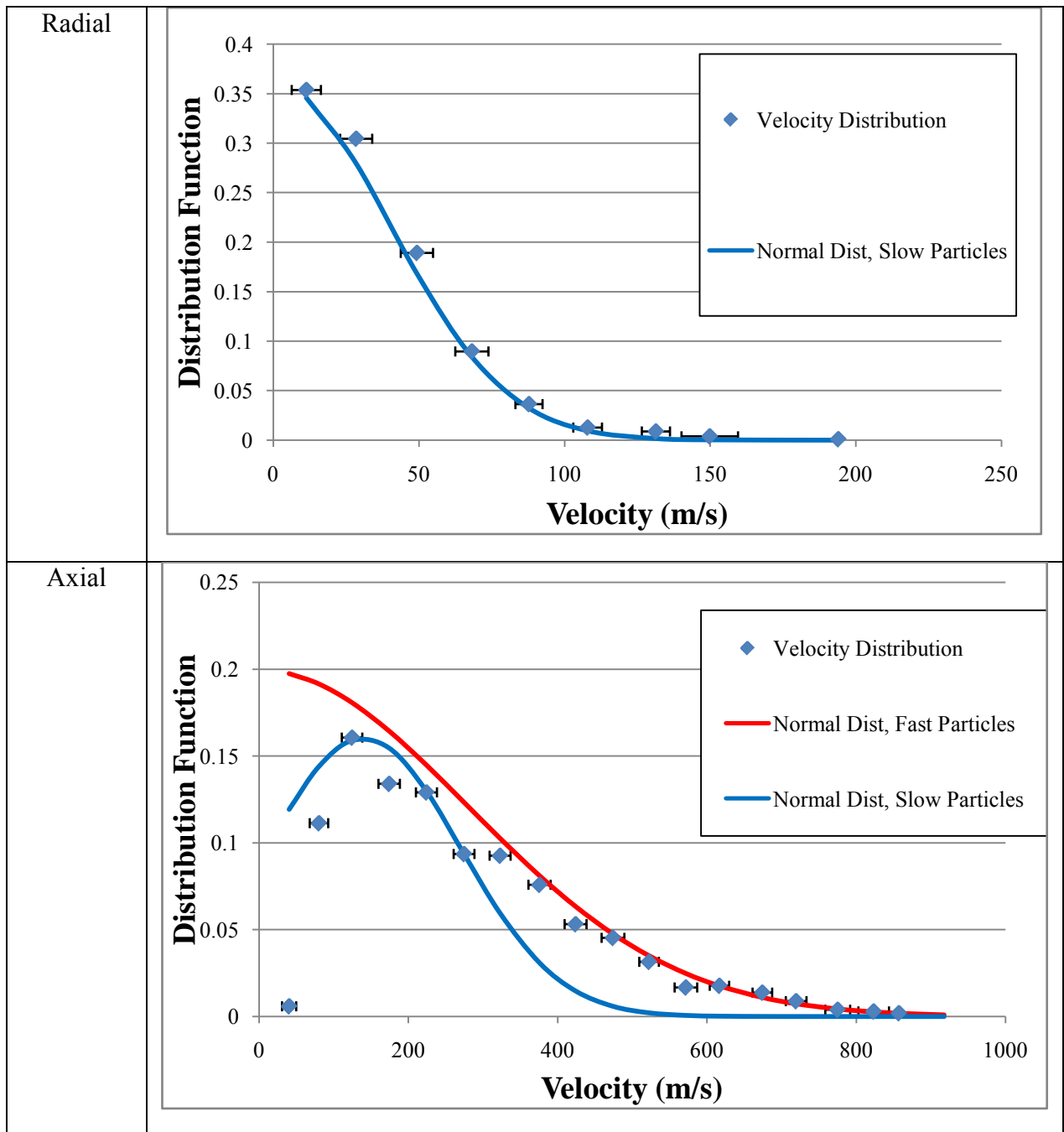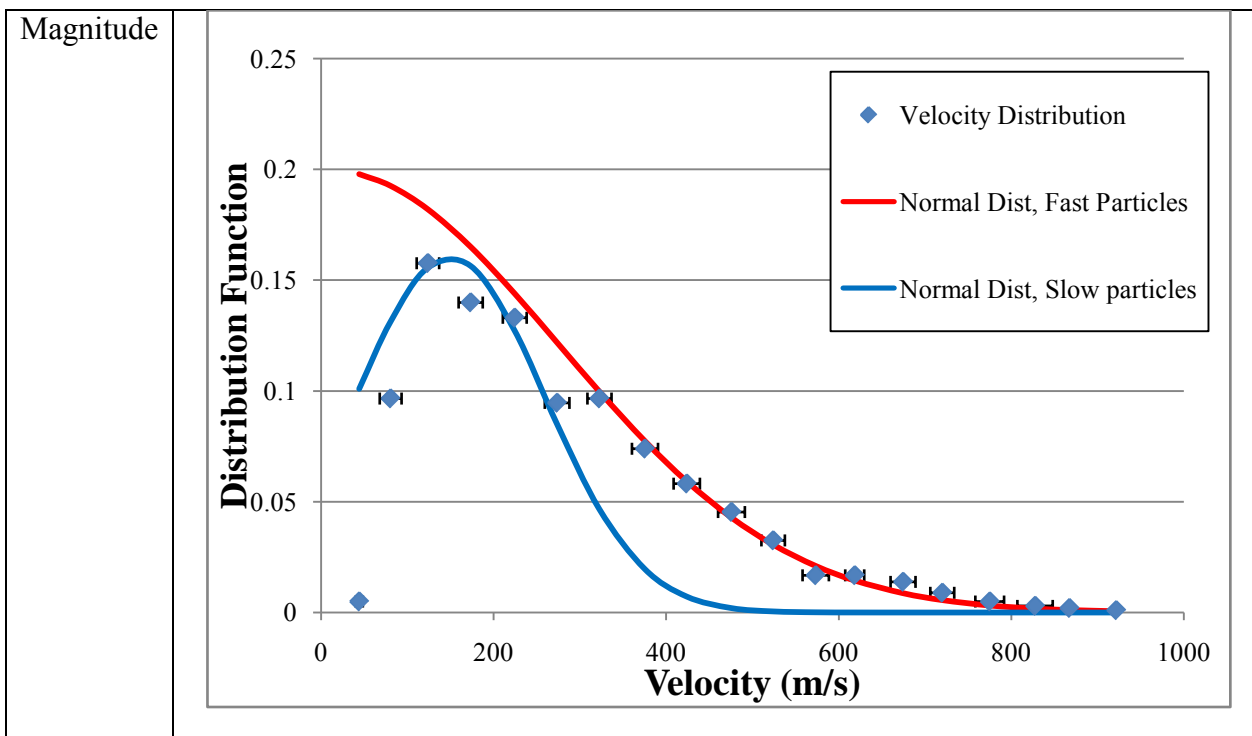
Figure 59 : Velocity Distribution for 7V (4 Joule)

8V (4.5 Joule)

Radial	

Axial	
Magnitude	
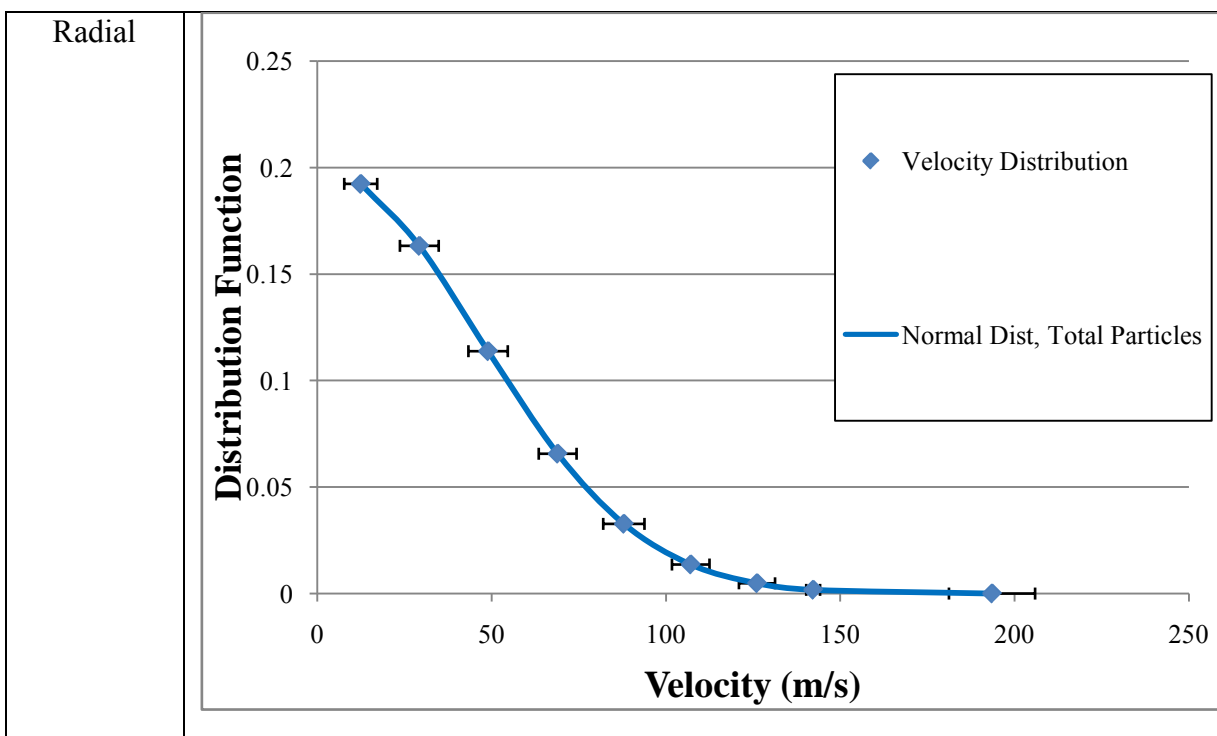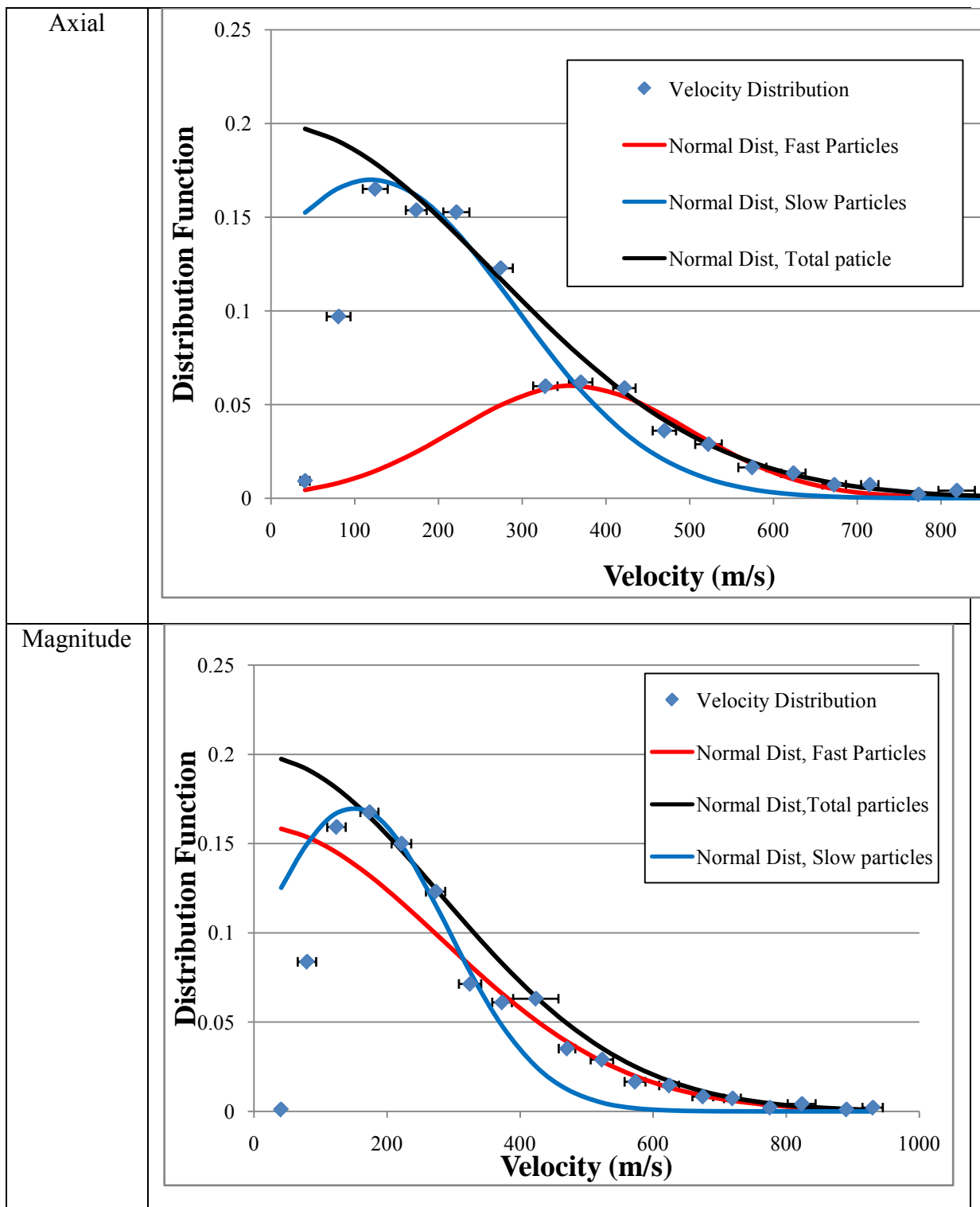
Figure 60 : Velocity Distribution for 8V (4.5 Joule)

Appendix C**: Angle Distribution for Each Energy Level**

5V (2.7 Joule)

| Slower than 200 m/s (46 % of total particles) | |
| Slower than 300 m/s (68% of total particles) | |

Faster than 300 m/s (32 % of total particles)	
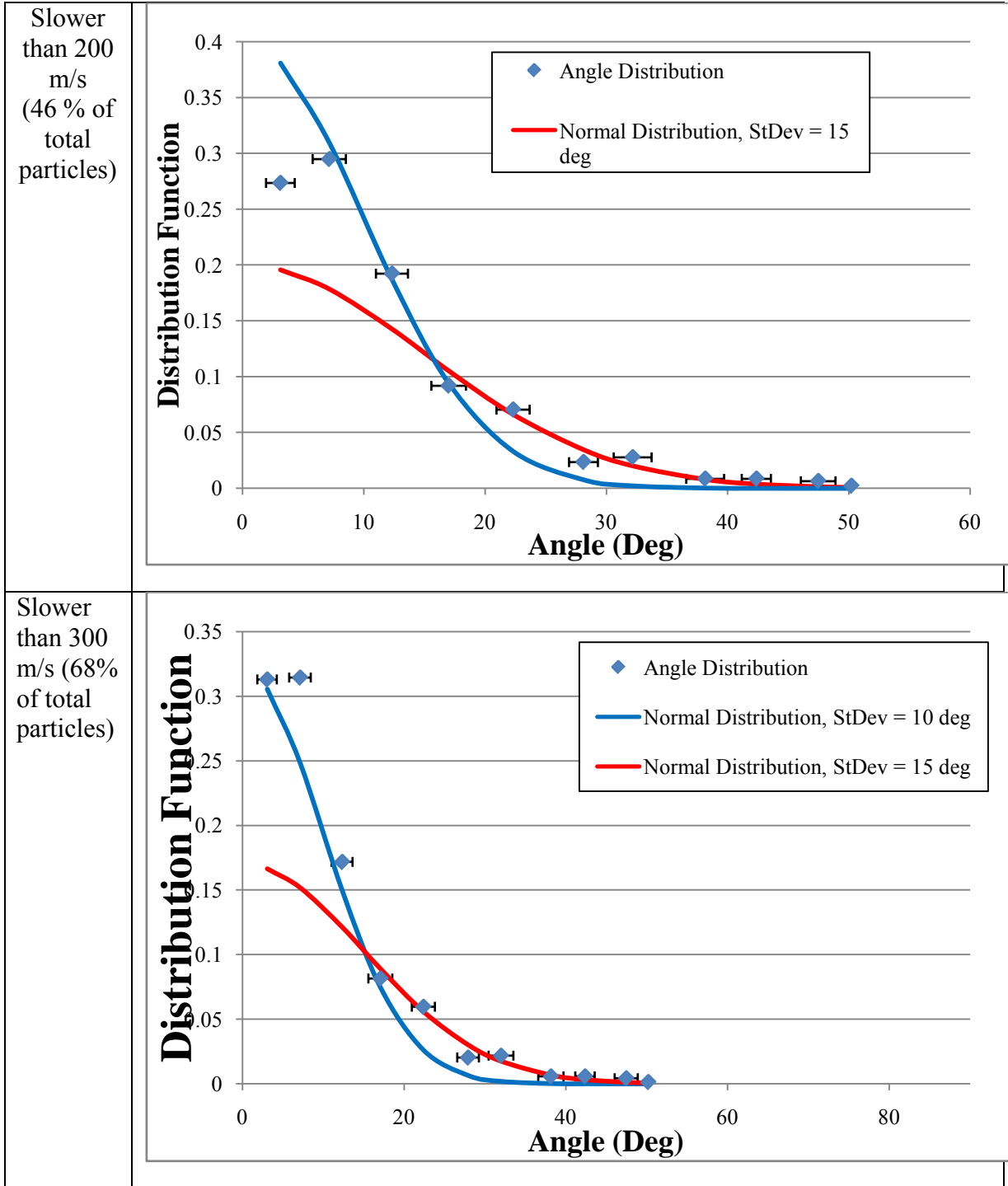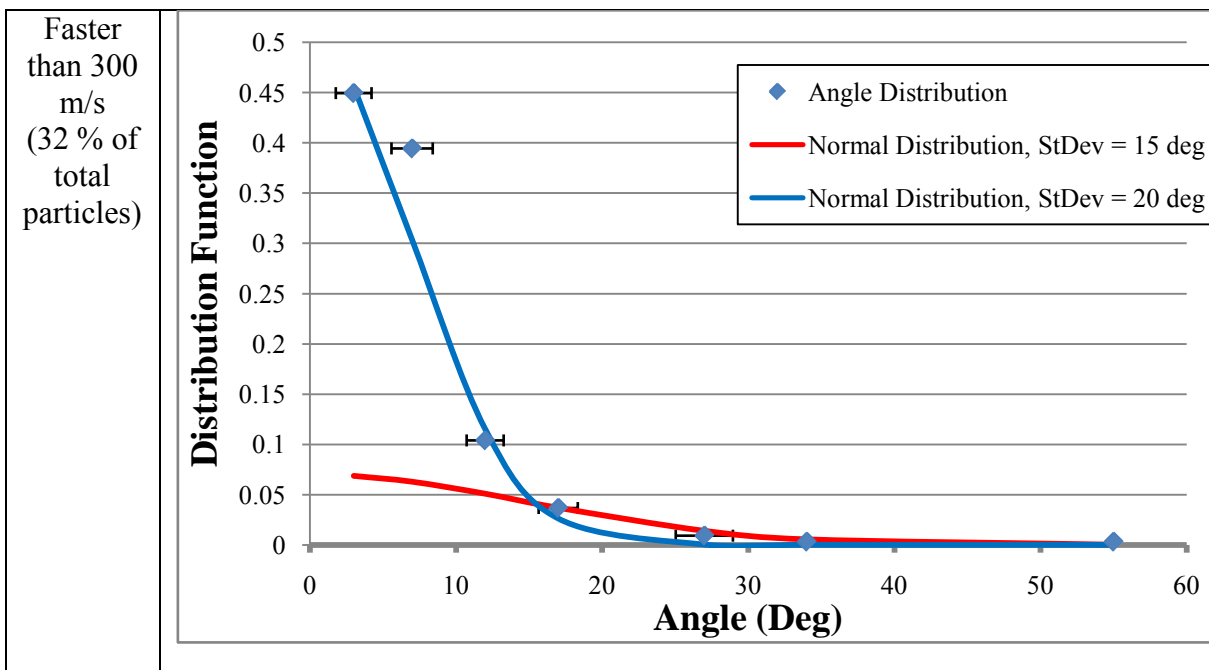
Figure 61 : Angle Distribution for 5V (2.7 Joule)

6V (3.4 Joule)

Slower than 200 m/s (28 % of total particles)	

93

| Slower than 300 m/s (50 % of total particles) | |

| Faster than 300 m/s (50 % of total particles) | |
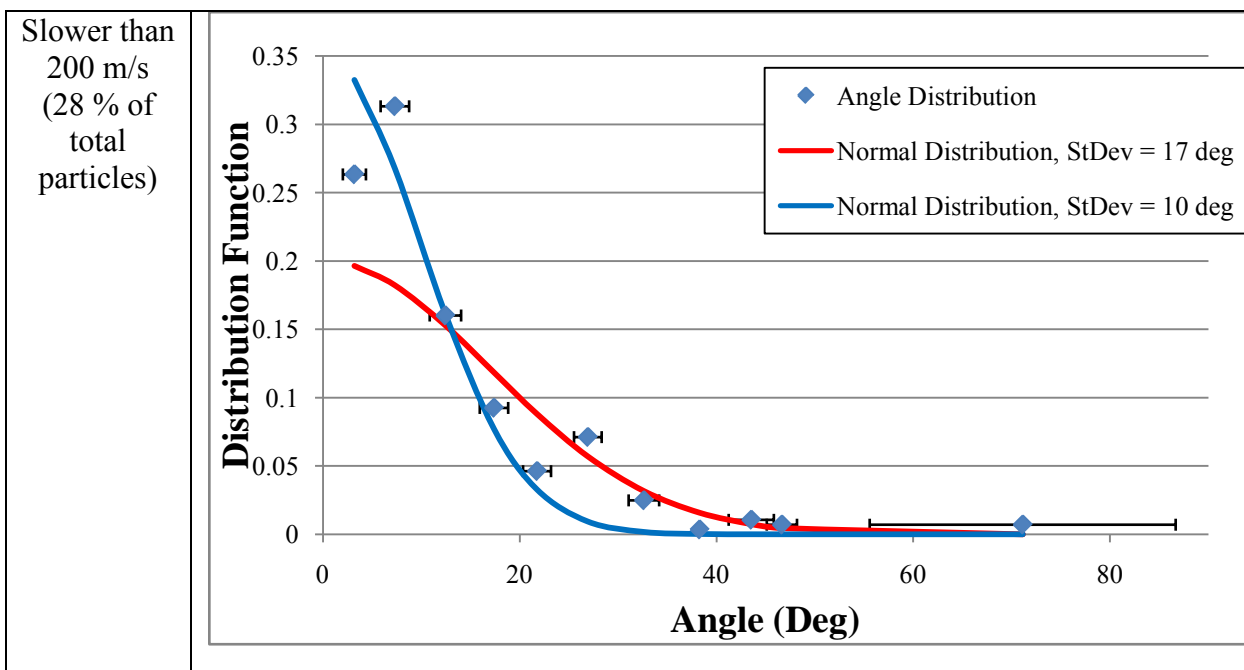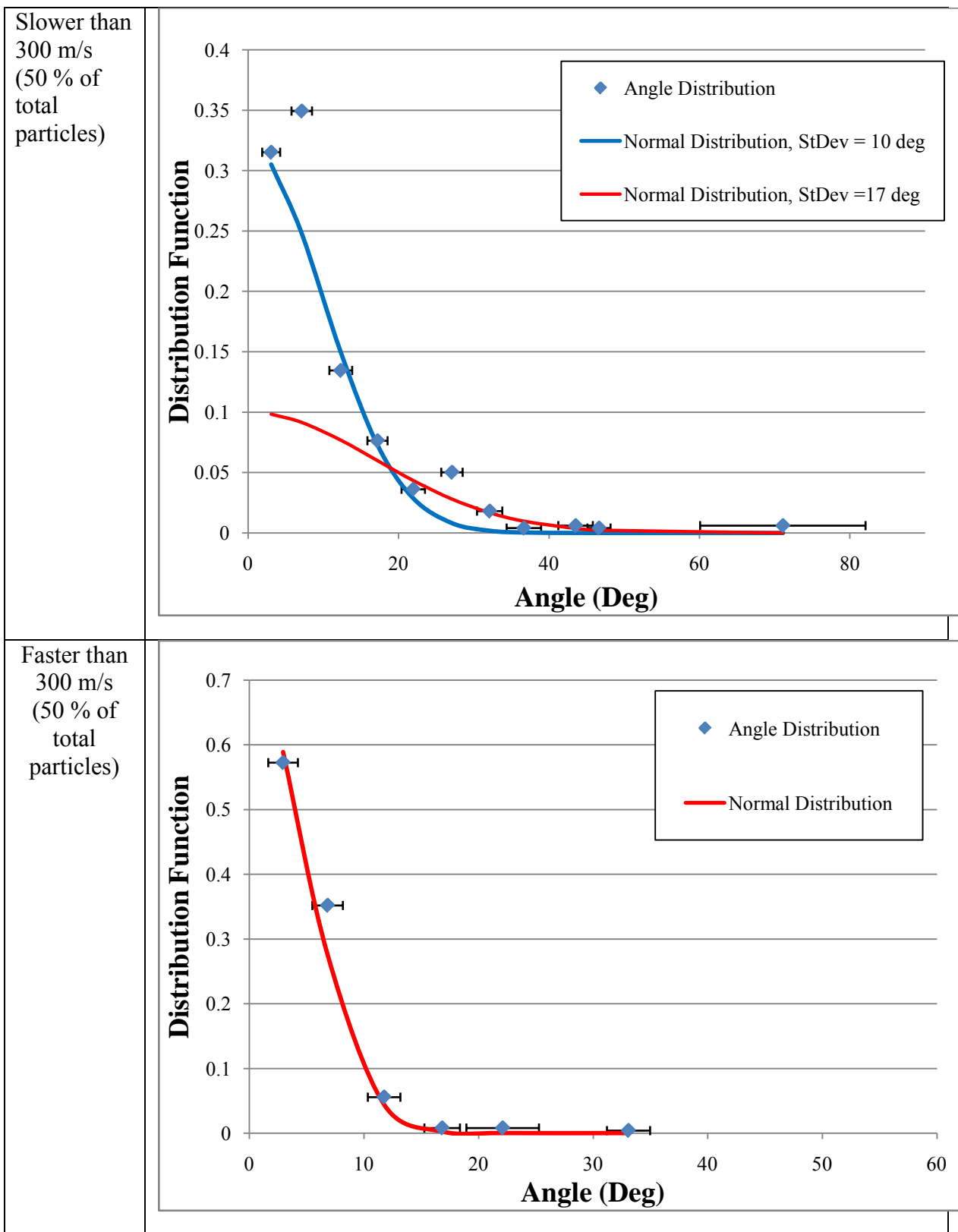
Figure 62 : Angle Distribution for 6V (3.4 Joule)

94

7V (4 Joule)

Slower than 200 m/s (40 % of total particles)	
Slower than 300 m/s (63 % of total particles)	

Faster than 300 m/s (37 % of total particles)	

Figure 63 : Angle Distribution for 7V (4 Joule)

8V (4.5 Joule)

Slower than 200 m/s (41 % of total particles)	

Slower than 300 m/s (68 % of total particles)	
Faster than 300 m/s (32 % of total particles)	
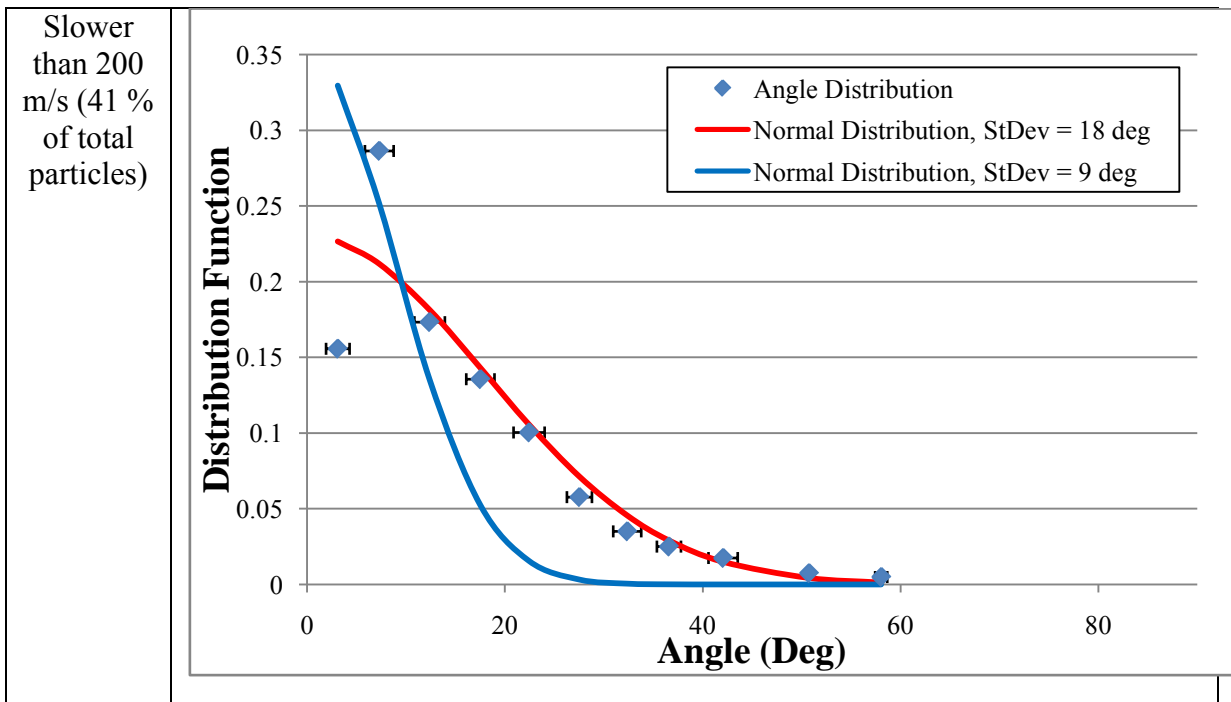
Figure 64 : Angle Distribution for 8V (4.5 Joule)

Vita

Captain Seo Myeongkyo graduated from R.O.K Air Force Academy in March
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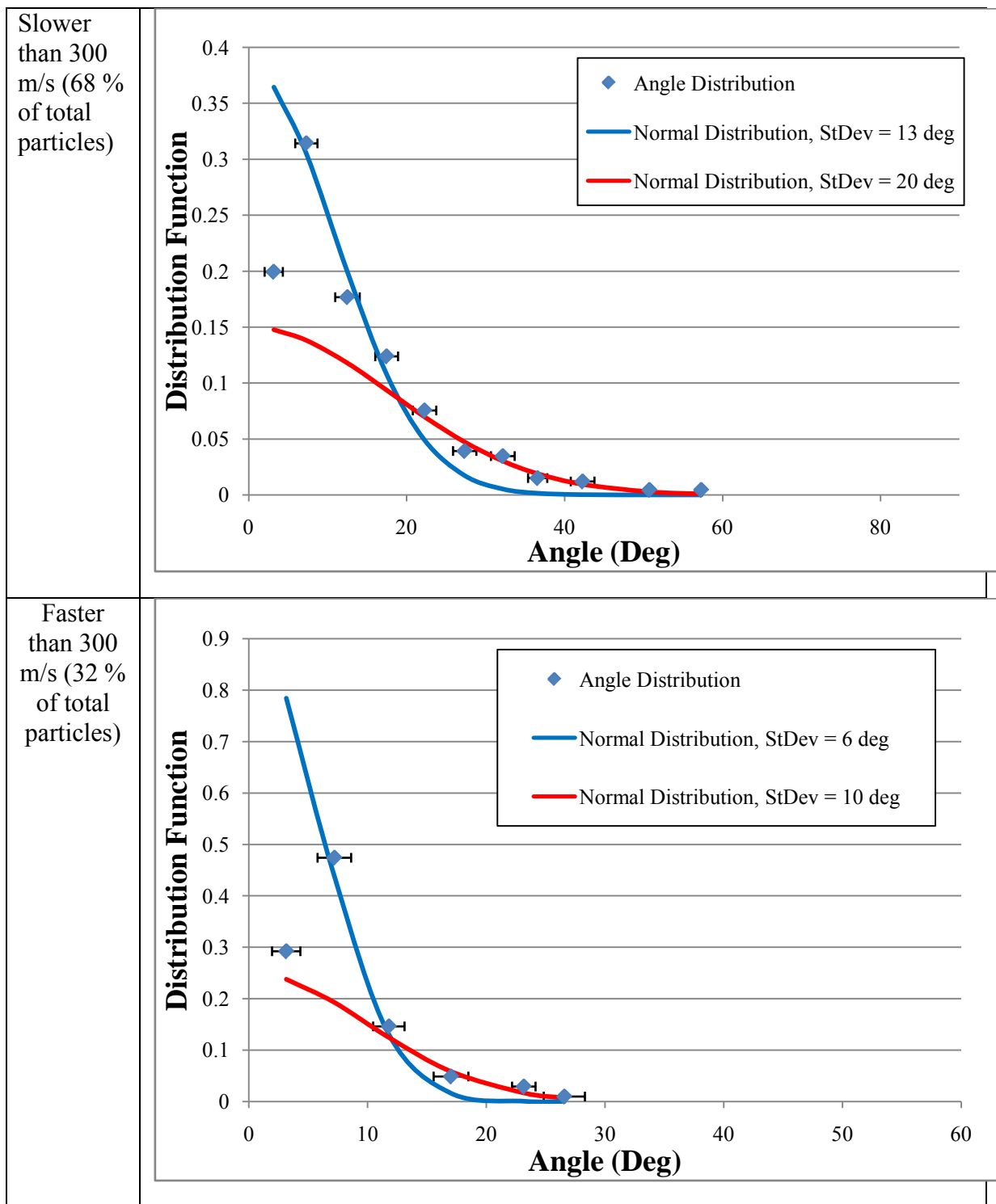[1] Christopher D. Rayburn, Mark E. Campbell, and A. Thomas Mattick "Pulsed Plasma Thruster System for Microsatellites", Journal Of Spacecraft And Rockets vol. 42, No. 1, January–February 2005

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14. ABSTRACT
Three-electrode micro-PPTs are a new version of two electrode micro-PPTs devices. Performance predictions and contamination expectations are essential characteristics needed by satellite designers. In order to focus on thruster specific impulse, thrust and efficiency, measuring the exhaust velocity or impulse bit and propellant consumption rate is essential. While this is not always possible to measure directly, focusing on the ejected mass from the PPT provides significant information allowing determination of these performance statistics. Specifically, focusing on exhaust angle distribution and velocity of the exhaust particles is the emphasis of this work. The results show that the three-electrode micro-PPT is more reliable than two-electrode micro-PPT and the operating energy range from 2 to 4.5 Joule is proper value to operate it. This research also shows that the angle distribution is similar to previous mass deposition distributions and the faster particles have shallower angles than that of slower particles. Finally, the energy did not give appreciable effect on angle and velocity distributions and have the Isp value range from 25 to 36 sec from the average exit velocity.

15. SUBJECT TERMS
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